Microalgae Carbon Fixation and Sinking Methodology for CO_2 Removal

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Contents

Glossary of terms

> **REMARK:** This glossary provides only the most important definitions for the current methodology. Please note that further definitions are listed in the Puro Standard General Rules.

Activity – A practice or ensemble of practices that take place on a delineated area resulting in emissions or removals taking place. For example, an Microalgae Carbon Fixation and Sinking (MCFS) activity refers to all operations within the activity boundary of a particular MCFS removal project. An eligible activity is an activity that meets the qualification criteria in a given certification methodology or protocol.

Air-Sea Gas Exchange (ASGE) - The bidirectional transfer of gases between the atmosphere and the surface ocean, driven by differences in partial pressure across the air-sea interface. MCFS activities create a negative perturbation in seawater CO_2 partial pressure that is re-equilibrated by a CO_2 flux from the atmosphere to the surface ocean via Air-Sea Gas Exchange.

Area of Interest (AOI) - The Area of Interest is the defined geographic region within which all project activities occur, including carbon removal, monitoring, and data collection. It is delineated by precise polygonal boundaries with geospatial coordinates and depth ranges, and is used for permitting, environmental assessment, and verification.

Deployment and Sinking Site – The Deployment and Sinking Site is a specific site within an AOI where Substrates are released and carbon is intended to be sequestered. It must meet strict criteria for depth, distance from shore, and long-term isolation from the atmosphere, and is separately recorded with its own geospatial boundaries. Many Deployment and Sinking Sites may exist with the same AOI.

Dissolved Inorganic Carbon (DIC) – The sum of inorganic carbon components in an aqueous solution, consisting of three main constituents: free CO_2 (aq), bicarbonate ions (HCO_3^-) and carbonate ions (CO_3^{2-}).

Dissolved Organic Carbon (DOC) – The portion of organic carbon found in water that is able to pass through a filter with a pore size between 0.22 and 0.45 μm.

Environmental baseline – The environmental conditions of the storage site prior to biomass deployment, to be established by the CO_2 Removal Supplier prior to deployment through the proper characterization of biological and geochemical properties of the water column and sediment.

External Operator – Any party (such as the Substrate sourcing operator, the logistics operators, or the storage site operator), operating on behalf of and at the direction of the CO_2 Removal Supplier for provision of services relating to the MCFS activity (however, not including the CO_2 Removal Supplier itself).

Leakage – An indirect effect associated to a CO_2 Removal activity and dependent on the selected Baseline, that may lead to an increase or decrease in greenhouse gas emissions or removals, outside of the system boundaries of the activity, if not avoided or mitigated.

Loss – The definition for loss applies to re-emission pathways known or assumed *a priori*, and which therefore need to be accounted for *at the time of CORC issuance*.

Output – Volume of CO_2 Removal within a certain Monitoring Period which is eligible to receive CORCs. CORCs are always issued for Net Carbon Dioxide Removal in the production process, which means that the total volume of Output is determined by subtracting the CO_2 emissions volume (generated directly or indirectly due to the production process or materials used, according to the applicable Methodology) from the CO_2 Removal volume.

Particulate Inorganic Carbon (PIC) – the fraction of carbon bound in mineral forms that exists as suspended or sinking particles in aquatic systems, distinct from dissolved inorganic carbon and organic carbon pools.

Particulate Organic Carbon (POC) – The portion of organic carbon found in water that remains on a filter after separation, typically corresponding to organic matter in particulate form (See also Dissolved Inorganic Carbon (DOC)).

Phytoplankton - Phytoplankton are microscopic, oxygenic photoautotrophs comprising photosynthesizing cyanobacteria and eukaryotic algae that act as primary producers.

Production Facility – An ensemble of physical assets necessary to perform the end-to-end activities associated with a CO_2 Removal activity, in the context of the Methodology. In the case of MCFS, the Production Facility comprises an infrastructure for Substrate production, logistic chain for Substrate transport, and one or several deployment and sinking sites (See Deployment and Sinking Site).

Reversal – An event which cancels, entirely or in part, the effects of an issued CORC. Reversal is an unaccounted-for event resulting in a situation where at least a part of the removed, quantified and certified carbon represented as a CORC is either released back into the atmosphere (re-emission, loss) or can no longer be considered safely and durably stored for a long term.

Sinking Efficiency - The fraction of carbon fixed through primary production that is transferred from the surface ocean to the seafloor.

Substrate - Engineered, nutrient-impregnated particles that provide a surface for algal colonisation in the euphotic zone equipped with a controlled sinking mechanism.

Tonne (t) – A unit of mass equivalent to 1000 kg, also known as 'metric tonne'. In this methodology, the word 'tonne' always refers to metric tonnes.

Acronyms

AOI – Area of Interest

ASGE – Air-sea gas exchange

CDR – Carbon Dioxide Removal

CORC – CO_2 Removal Certificate

DIC – Dissolved Inorganic Carbon

DMSP – Dimethylsulfoniopropionate

DOC – Dissolved Organic Carbon

EEZ – Exclusive Economic Zone

EHS – Environment, Health and Safety plan

EIA - Environmental Impact Assessment

EIO-LCA – Economic Input-Output Life Cycle Assessment

GHG – Greenhouse Gas

HNLC – High-Nutrient Low-Chlorophyll

IPCC – Intergovernmental Panel of Climate Change

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

mCDR – Marine Carbon Dioxide Removal

MCFS – Marine Carbon Fixation and Sequestration

MLD - Mean Layer Depth

NPZD – Nutrient-Phytoplankton-Zooplankton-Detritus

PAR – Photosynthetically Active Radiation

PIC – Particulate Inorganic Carbon

POC – Particulate Organic Carbon

pCO2 – CO_2 Partial Pressure

SDGs – Sustainable Development Goals

TA – Total Alkalinity

tCO_2e – Tonnes of CO_2 equivalents

Note to the reader

REMARK: This methodology provides general information as well as actual requirements which must be met by all projects seeking certification under the Puro Standard. Across the entire methodology, the requirements correspond to numbered rules with formatting conforming to the below example.

0.0.1 This is an example of a numbered rule. The requirements set within numbered rules must be followed by all projects seeking certification under the Puro Standard.

Please note that in addition to the requirements of this methodology document, all projects seeking certification under the Puro Standard must also comply with the Puro Standard General Rules and other Standard Requirements, as well as any applicable local laws, regulations, and other binding obligations.

For Puro Standard documents, see the Puro Standard documents library.

1. Introduction

1.1. Overview and scope

This methodology sets the requirements for eligibility and quantification of net CO_2 removal attributable to Microalgae Carbon Fixation and Sequestration (MCFS) project activity.

In this methodology, the MCFS refers to a pathway which captures and sequesters carbon through additional photosynthetic activity of local phytoplankton in the surface ocean and on designated Substrates, followed by an intentional and controlled export of that carbon to the deep ocean and ocean sediment, resulting in durable carbon storage over two hundred (200)[1] years.

In broad terms, the scope of this methodology includes the following fundamental components: Substrate manufacturing, transportation, deployment and storage. Certain process steps allow for several different variations, which are further elaborated in section 3.

Primary production - the fixation of CO_2 into organic matter by photosynthetic organisms such as phytoplankton - is a natural biological process influenced by a multitude of biological, chemical, and physical factors. Light availability, nutrient supply, and phytoplankton community structure are fundamental drivers of primary production in the global oceans.

Almost all the organic matter produced in the surface oceans by primary production is eventually consumed and respired to inorganic carbon. Thus, organic matter export to sediments represents only a very small fraction of global phytoplankton production (~1%) (Middelburg, 2019). The natural sinking rates of marine organic matter depend on numerous factors such as size and density, oceanographic conditions such as temperature and currents (Omand et al., 2020), and aggregation and disaggregation (Burd et al., 2010; Collins et al., 2015; Giering et al., 2014). Larger, denser particulate matter tends to sink faster, as their gravitational pull is stronger.

MCFS involves **both** 1) an increase in primary productivity of local phytoplankton attributable to the project activity, for instance through the addition of micronutrients and 2) an enhancement of the efficiency of carbon export to the deep ocean and sediments for durable storage attributable to the project activity, for instance through the addition of mechanism that promotes sinking, or the use of Substrates and other inputs (see section 1.4 for further details regarding the sinking mechanism)[2]. Under this methodology, only the CO_2 equivalents originating from the additional, sunk phytoplankton, are quantified towards carbon removal. The quantification of the overall gross amount

[1] CO_2 must be sequestered (on a net basis) for *at least* 200 years.

[2] For avoidance of doubt, this methodology does not apply for ocean iron fertilization (OIF) approaches. While OIF - defined as an addition of small amounts of iron to the surface water to stimulate algal blooms - meets the first criteria, it doesn't meet the second as it lacks additional sinking mechanisms. The methodology clarifies additional requirements and criteria that differentiate MCFS from OIF or other interventions.

of CO_2 equivalents stored is based on how much the project activity increases the total carbon stored in the deep ocean and thus increases the flux of CO_2 from the atmosphere into the deep ocean during the monitoring period (see section 5 and section 6).

1.2. Natural carbon cycle and mechanism for CO_2 removal

The ocean is by far the largest reservoir of carbon dioxide in the climate system that exchanges readily with the atmosphere, containing ~60 times more CO_2 than the atmosphere and ~18 times more than the terrestrial biosphere (DeVries, 2022). The ocean contains multiple forms of organic and inorganic carbon.

- Organic carbon in the ocean is found in two forms:
    - Solid-phase organic carbon that is incorporated into living organisms' soft tissues, which is referred to as Particulate Organic Carbon or POC.
    - Aqueous-phase organic carbon that is derived from the decomposition of particulate organic matter in the water column by microorganisms, which is referred to as dissolved organic carbon or DOC.
- Inorganic carbon in the ocean includes:
    - Solid-phase inorganic carbon in the shells of carbonate-producing plants and animals (referred to as Particulate Inorganic Carbon or PIC).
    - Dissolved CO_2 and its derivatives including Carbonic acid (H_2CO_3), bicarbonate ions (HCO_3^-), and carbonate ions (CO_3^{-2}), which are collectively referred to as Dissolved Inorganic Carbon or DIC.

There are three main mechanisms impacting the amount of total carbon stored in the ocean: solubility pump, organic biological pump and carbonate counter pump.

Solubility pump

The solubility of CO_2 in seawater increases as the temperature decreases (Weiss, 1974). In other words, cold water absorbs more CO_2 than warm water does. Atmospheric CO_2 is absorbed by the cold ocean water at high latitudes, commonly referred as the "thermodynamic pump" or the "solubility pump", and is particularly efficient in the cold surface waters that sink to form deep ocean waters. During their journey in the abyss, the deep waters are further enriched in CO_2 by the degradation of organic carbon by bacteria. When these waters upwell at the surface, they are very rich in CO_2 and DIC. The global mean air-sea CO_2 flux exhibits a distinct pattern (Takahashi et al., 1997). Warmer surface waters at low latitudes release CO_2 into the atmosphere as a result of global ocean currents and mixing, whereas colder surface waters at the poles absorb more atmospheric CO_2 (Gruber et al., 2023; Roy-Barman & Jeandel, 2016).

Organic biological pump

Photosynthesis converts dissolved CO_2 into particulate organic carbon which can be isolated from the atmosphere by sinking into the deep ocean, a process known as the "organic biological pump". In pulse photosynthetic events, the increase in photosynthetic carbon fixation will deplete dissolved inorganic carbon (DIC) in the surface ocean. This will cause the surface ocean to become undersaturated with CO_2 relative to the atmosphere, prompting the natural air-sea gas exchange process to draw in atmospheric CO_2 over the course of several months (Jones et al., 2014). A fraction of the carbon fixed through photosynthesis is exported from the surface ocean as "export production". The primary export mechanism involves the gravitational sinking of organic matter. Additionally, active transport by migrating organisms and vertical mixing of the water column contribute to carbon export (Boyd et al., 2019; Heinze et al., 1991; Sarmiento & Gruber, 2006; Siegel et al., 2023; Stukel et al., 2023; Volk & Hoffert, 1985). Yet by the time this organic carbon reaches the deep layers in the ocean, only about 1% of the original content remains in solid phase and settles to the sediments (Dunne et al., 2007; Hayes et al., 2021; Martin et al., 1987; Stukel et al., 2023) and is removed from the oceanic carbon cycle for geological timescales. The natural low export and sequestration efficiencies are the combined result of low sinking rates of the particulate organic matter and bacterial remineralization that degrades the organic matter in the water column.

Carbonate counter pump

The "carbonate counter-pump" corresponds to the formation of biogenic calcium carbonate ($CaCO_3$) in near surface waters, and its downward export (primarily by gravitational sinking) and subsequent dissolution in deep waters. The formation of biogenic calcium carbonate in surface water causes a net release of CO_2, increase in ocean acidification, as well as a decrease in alkalinity. Hence, the formation of this material acts to increase the partial pressure of CO_2 (pCO_2) in surface water (Holligan & Robertson, 1996), counteracting the effect of the organic biological pump.

The MCFS pathway enhances the organic biological pump to increase the amount of phytoplankton that grows in the surface ocean and sinks to the deep ocean and sediments. This results in a net increase in the amount of carbon stored in the ocean as POC, DOC, PIC, and DIC (the ratio of these carbon forms depends on the specifics of the project activity and ocean conditions), and a resulting net flux of CO_2 from the atmosphere to the ocean during the duration of the project.

1.3. Natural phytoplankton carbon capture mechanism

To ensure net carbon removal, the project activity shall increase phytoplankton primary productivity and the resulting carbon storage in excess of the baseline. To ensure environmental safety, the additional phytoplankton growth shall include only local phytoplankton species. For avoidance of doubt, the use of external, lab-grown or otherwise imported phytoplankton, is excluded from this methodology.

Phytoplankton are the main contributors to photosynthesis in the ocean. Their small size gives them a high surface area to volume ratio, which makes nutrient uptake very efficient (Falkowski, 1994; Marañón, 2015). The abundance and species composition of phytoplankton communities vary significantly over space and time. These fluctuations are driven by the local bottom-up factors (e.g., light and nutrient availability) and top-down factors (e.g., zooplankton grazing).

The microbial food web is a complex network of interactions between microorganisms, including bacteria, archaea, fungi, protists, and viruses. Phytoplankton, as the primary producers, form a crucial link within this web. Phytoplankton release organic matter either directly or through grazing and cell lysis, which becomes a key food source for heterotrophic bacteria. These bacteria are then consumed by protozoa (like flagellates and ciliates), which in turn are eaten by larger zooplankton, transferring the energy initially fixed by phytoplankton up the food chain. This intricate network of interactions within the microbial food web, driven by the primary production of phytoplankton, supports the entire marine ecosystem and its biogeochemical cycles.

The major nutrients (macronutrients) required by phytoplankton are nitrogen (nitrate, nitrite, ammonium) and phosphorus (phosphate). In some cases, silica is also required. Trace elements (micronutrients) such as iron, manganese, cobalt, zinc, and copper are also needed. These nutrients occur naturally in varying amounts in seawater and are often the limiting factors for phytoplankton growth and production, as they are not distributed evenly throughout the global ocean (Moore et al., 2013). Surface waters are typically nutrient-poor, as phytoplankton and bacteria quickly utilize nutrients as they become available (Moore, 2016). Sinking organic matter (e.g. zooplankton fecal pellets, carcasses) is decomposed and releases nutrients back into the water column ("remineralization"), resulting in higher nutrient concentrations in deeper water. Water column density stratification limits the mixing of nutrient-rich deep water with surface water. However, upwelling of deep water does occur in certain areas (e.g. Pacific Ocean eastern boundary, equatorial upwelling zones, etc. (Bograd et al., 2023; Kessler, 2006; Morrison et al., 2015), resulting in high productivity in surface waters due to the influx of macronutrients.

The representative stoichiometric composition for phytoplankton biomass is $C_{106}H_{175}O_{42}N_{16}P$, and is known as the Redfield ratio, which describes the ratio of the most prominent chemical elements present in phytoplankton biomass (Tyrrell, 2001). The photosynthesis and remineralization reactions that contribute to biomass growth can be represented as follows:

$$106\, CO_2 + 16\, HNO_3 + H_3PO_4 + 78\, H_2O \rightleftharpoons (C_{106}H_{175}O_{42}N_{16}P) + 150\, O_2$$

The vertical distribution of chlorophyll, phytoplankton physiology, and varying nutrient concentrations interact to shape community composition and primary production rates. Solar radiation, climatic patterns, and oceanic conditions together drive annual fluctuations in net primary production (Lutz et al., 2007).

Phytoplankton abundance and productivity are primarily determined by the availability of light and nutrients. Light is required for photosynthesis, and phytoplankton are therefore limited to the uppermost layers of the ocean where light is abundant and typically ranges from 50-200 m deep (Kirk, 2010). Light intensity also varies seasonally in high latitudes, causing seasonal variations in both phytoplankton community composition and primary production rates (Uitz et al., 2010).

1.4. Natural export of carbon to the deep ocean

Naturally, the majority of organic matter produced in the surface oceans by primary production is eventually consumed and respired to inorganic carbon. Only a small fraction is preserved via burial in accumulating sediments (~0.2–0.4 Pg y−1), compared to the total phytoplankton production (~50 Pg C y−1; (Middelburg, 2019). Net community production (NCP) is the difference between inorganic carbon fixation by primary production and the consumption/respiration of organic carbon by heterotrophs in the euphotic zone. This production is exported to the deep ocean as sinking aggregates in the export flux. These aggregates, which can be quantified as particulate organic carbon (POC), vary in size and composition. POC exported from the surface ocean decreases with depth due to consumption by filter feeders and bacteria, and conversion of some organic matter into dissolved organic carbon (DOC) by particle-attached microbes. The natural sinking rates of sinking aggregates are influenced by factors such as particle size and density, particle aggregation and disaggregation (Burd et al., 2010; Collins et al., 2015; Giering et al., 2014) and oceanographic conditions like temperature and currents (Omand et al., 2020). Larger, denser particles sink faster due to stronger gravitational effects.

The quantity of POC reaching the deep ocean and ultimately settling into seafloor sediments is directly influenced by the efficiency of the biological carbon pump. A highly effective biological pump is characterized by both a large amount of carbon leaving the surface ocean and a substantial portion of that carbon reaching deeper depths (Buesseler et al., 2020; Buesseler & Boyd, 2009; Kienast & Torfstein, 2022). Export efficiency quantifies the proportion of organic carbon produced by phytoplankton in the light penetrating surface ocean that sinks to deeper waters. High export efficiency and high primary production regimes are rare and may be linked to non-biological particle export. A biome-scale analysis showed that the factors influencing export efficiency differ on regional and global scales (Henson et al., 2019).

The seasonal variability of carbon export and primary production differs across latitudes. In lower latitudes, carbon export tends to fluctuate more seasonally than primary production, while the opposite is true in higher latitudes. These regional differences suggest distinct underlying mechanisms governing the relationship between production and export (Lutz et al., 2007). Physical factors such as temperature, light penetration, ocean circulation, nutrient availability, and mixing play crucial roles in shaping these patterns. Warmer temperatures can accelerate metabolic processes, potentially reducing carbon export efficiency, while colder temperatures may favor carbon storage

(Boyd et al., 2019; López-Urrutia et al., 2006). Latitude-dependent light variation and water clarity influence phytoplankton growth and carbon fixation. Ocean currents and nutrient dynamics impact both production and export. These factors collectively influence plankton community composition, phytoplankton degradability, zooplankton behavior, and particle dynamics, ultimately affecting the efficiency of the biological carbon pump.

The biological carbon pump's impact on atmospheric CO_2 levels hinges on both the amount of carbon exported from the surface ocean (essentially removing CO_2 from the fact carbon cycle), the duration it remains sequestered in the deep ocean (durability; (Siegel et al., 2021), and the efficacy of the air-sea gas exchange, which governs the transfer of CO_2 between the ocean and atmosphere (Nowicki et al., 2024). As the Microalgae Carbon Fixation and Sinking approach is based on the removal of carbon from the surface waters, where biomass growth is facilitated by the consumption of carbon dissolved in seawater, which in turn creates a deficit relative to the atmosphere and induces reabsorption of atmospheric CO_2 by the ocean, it is imperative to account for the efficiency of the carbon-depleted surface water to efficiently uptake additional atmospheric CO_2. For the purposes of this methodology, the net CO_2 captured and sunk by an MCFS activity must in all cases account for the air-sea gas exchange efficiency for the carbon to be considered durably removed (see section 6.1).

The organic biological carbon pump's ability to export carbon is limited, with merely 1% reaching the sediments. The inefficiency of this process is dictated by slow sinking resulting in long residence time of the POC in the water column (Herndl & Reinthaler, 2013; Omand et al., 2020) and consequently, the long period of remineralization it experiences. Rapid sinking of organic matter to the sediment can increase carbon export from the surface ocean and augment the overall efficiency of the biological carbon pump.

1.5. Enhanced phytoplankton growth and export

MCFS enhances the export of carbon fixed by local phytoplankton to the deep ocean and sediments. This can be achieved using a Substrate that floats in the photic zone and contains a nutrient cocktail, promoting phytoplankton growth and carbon fixation. A sinking trigger then propels the Substrate to the deep ocean for long-term storage (figure 1.1).

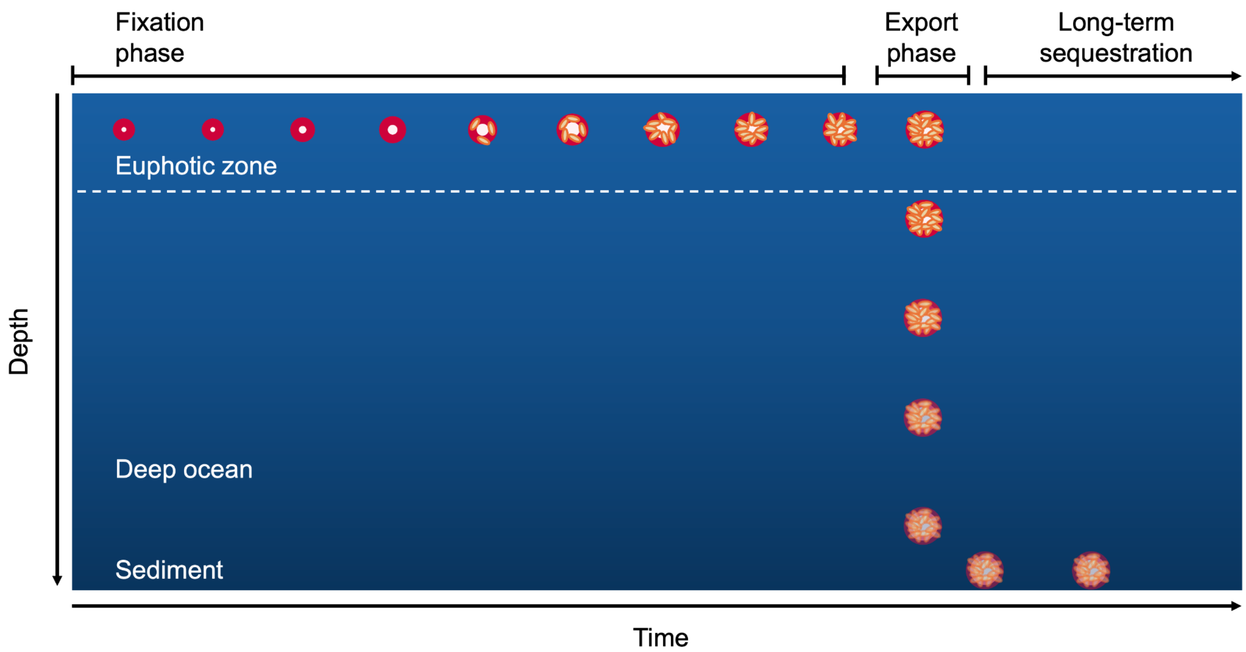

Figure 1.1. Schematic illustration of the phytoplankton growth on the Substrate (red particles at the onset of the fixation phase) and subsequent export into the deep ocean and sediment. During the fixation phase, microalgae (orange) start to accumulate on the Substrates. At the export phase, the Substrates and the accumulated microalgae and adjacent bacteria (fixed carbon) sink to the deep ocean, where the carbon is sequestered for at least 200 years. Note, that this figure illustrates the capture and sinking process only, and does not account for the factors impacting the sequestration efficiency. For further details on the quantification of net CO_2 Removal, see section 5.

MCFS can be applied in certain open ocean areas, characterized as HNLC, where benthic conditions and ocean circulation patterns support long-term carbon sequestration of 200+ years (see also section 3.7). MCFS activities can be strategically deployed during optimal environmental conditions (target season and location), where net primary productivity due to the project activity is expected to be highest, determined by e.g. the Truscott-Brindley (TB) model (Truscott & Brindley, 1994). Simulations can determine time-dependent population sizes of phytoplankton and zooplankton grazers and evaluate the lag time between phytoplankton growth and zooplankton grazing to maximize net carbon fixation efficiency.

Before deployment, the dispersion of Substrates by natural currents can be modeled to inform the selection of optimal sites and guide the overall deployment strategy. By leveraging historical data and utilizing forecast-coupled physical models alongside particle tracing models, ocean currents, wave dynamics, and wind patterns can be predicted. This allows for the identification of optimal deployment locations and ensures that the fixed carbon is naturally transported toward the intended target area. The geo-optimization approach enables efficient placement of Substrates at designated sinking locations, thereby enhancing the capacity to predict their trajectory and eventual settlement to the ocean floor. This ensures the sufficient distribution of Substrates, promoting effective nutrient availability for photosynthesis and durable storage sites.

1.6. Eligible deployment areas

Phytoplankton activity and abundance are often limited by the depletion of nutrients in the upper ocean. Large-scale spatial patterns of limiting nutrients (Moore et al., 2013) have been inferred from multiple lines of evidence. Absolute concentrations of surface nutrients, or their stoichiometric ratios, indicate the potential for limitation or deficiency, respectively. Surface inorganic nitrogen and phosphorus concentrations are highly depleted throughout much of the low-latitude oceans, due to a combination of physical water stratification and biological uptake. These regions, often referred to as oligotrophic gyres, cover vast expanses of the tropical and subtropical ocean (Sarmiento & Gruber, 2006). Availability of the macronutrients phosphorus (P) and nitrogen (N) can limit phytoplankton growth in different oceanic regions. Surface depletion of micronutrients, such as iron (Fe), cobalt (Co), zink (Zn), copper (Cu), nickel (Ni) and cadmium (Cd), is also observed in many regions (Deutsch et al., 2007; Ho et al., 2003; Morel & Price, 2003) that are typically referred to as High Nutrient Low Chlorophyll (HNLC) areas.

High Nutrient, Low Chlorophyll (HNLC) areas are ocean regions that defy the usual connection between nutrient availability and phytoplankton productivity, as they have high macronutrient concentrations but low phytoplankton biomass and chlorophyll levels. These areas, encompassing 20-30% of the global ocean, include the Subarctic North Pacific (SNP), the Eastern Equatorial Pacific (EEP), and the Southern Ocean (SO). The limited phytoplankton growth in HNLC areas, despite abundant nutrients, results in low chlorophyll levels. This is primarily due to micronutrients deficiency in surface waters. Compared to other ocean regions, HNLC areas exhibit reduced variability and high temporal persistence (Basterretxea et al., 2023; Boyd & Ellwood, 2010). These areas have substantial potential for carbon sequestration through primary production by supplying the limiting nutrients to the local phytoplankton in the area.

The scope of the MCFS methodology strictly limits all deployments to HNLC areas. For further details, see section 3.7.

1.7. Ocean circulation and its impact on CO_2 removal

The effectiveness of the Microalgae Carbon Fixation and Sinking approach is dependent on the efficiency of the enhanced phytoplankton growth on the Substrate and the capacity to efficiently increase the carbon export to the deep ocean above the natural baseline, as well as the sinking site conditions. Specifically, parameters such as depth, downstream circulation patterns and ocean ventilation timescales impact the durability and net efficacy of the Microalgae Carbon Fixation and Sinking approach (Nowicki et al., 2024; Siegel et al., 2023). In general, deeper sites will sequester the stored carbon for much longer timescales than shallow sites, with median sequestration times reaching decadal or centennial timescales (Boyd et al., 2019; Siegel et al., 2021).

Therefore, achieving durable removal of atmospheric CO_2 hinges on the transfer of biomass carbon into the deep ocean, where it may be stored for centuries to millennia either as dissolved inorganic carbon (DIC) in deep waters or as buried carbon in seafloor sediments—both outcomes shaped by biogeochemical dynamics at the water-sediment interface and deep ocean circulation. Characterized by high pressure, low temperatures, and often limited oxygen, the deep-sea environment slows microbial metabolism, slowing down, but not halting, the decomposition of organic matter (Canfield et al., 1993; Franco-Cisterna et al., 2024; Tamburini et al., 2003). While these conditions delay degradation, the vast majority of sinking biomass is still remineralized into dissolved inorganic carbon (DIC), which accumulates in deep waters and is isolated from the atmosphere on timescales of centuries to millennia (Ricour et al., 2023). The deep ocean is thus an important, and largely transient and dynamic, carbon sink. A smaller fraction of organic carbon escapes decomposition and is buried in sediments, contributing to more permanent sequestration. The fate of DIC is shaped by deep ocean circulation, which governs the eventual return of DIC-rich waters to the surface and their potential re-release back to the atmosphere."

The "first-passage time", also known as “residence time” or "ventilation time”, is defined as the time it takes for a parcel of deep ocean water to make its first contact with the surface ocean and atmosphere (Primeau, 2005). This time varies across different latitudes and ocean basins but follows a consistent general pattern (DeVries & Primeau, 2011; Gebbie & Huybers, 2012; Khatiwala et al., 2009). While the depth at which organic matter is remineralized influences how long the resulting DIC is likely to remain isolated from the atmosphere, the ocean region determines the circulation pathways and timescales that govern its eventual re-exposure.

(Siegel et al., 2021) discussed the global pattern of carbon retention versus depth over a 100-year time horizon for simulated DIC injections. When carbon was introduced below 1,000 m, substantial retention occurred in part of the areas, with timescales extending into centuries and more. The Pacific Ocean is known for having some of the oldest deep-water masses in the global ocean (Kawasaki et al., 2022). Time to surface re-exposure of ocean deep waters is generally smaller in the Atlantic Ocean (600-1000 years) than in the Pacific Ocean (1000-1400 years). It appears to increase northwards (i.e. longer time in North Pacific vs South Pacific). The Pacific, particularly its northern region, is thought to be the terminus of the global ocean circulation deep branch and therefore experiences weaker overturning circulation (Holzer et al., 2020). Transporting organic carbon to such deep-water masses facilitates long-lasting carbon storage.

A dense, carbon-bearing Substrate that sinks rapidly and settles at targeted deep-sea sites can facilitate long-term carbon removal. Once deposited, the organic matter undergoes slow decomposition and remineralization, moderated by the cold, high-pressure, and often low-oxygen conditions of the deep-sea floor. If incorporated into marine sediments the organic matter can be preserved through burial for extended timescales (Jørgensen et al., 2022). Further decomposition products can potentially dissolve into the sediment pore water and surrounding deep waters with their fate determined by biogeochemical processes that can be evaluated through modeling and in-situ or ex-situ experiments.[3]

1.8. Oceanographic modeling

Once decomposition products, such as DIC, enter the deep ocean through remineralization or dissolution, their fate is governed by large-scale ocean circulation. The movement of these water masses, and the time they remain isolated from the atmosphere, are fundamental to determining the durability of carbon sequestration. The first-passage time (or residence time) represents the interval between a water parcel's entry into the deep ocean and its first return to the surface, where exchange with the atmosphere becomes possible. These timescales vary regionally, from decades to thousands of years, depending on the structure of the global circulation patterns and local regional physical dynamics (DeVries & Primeau, 2011; Gebbie & Huybers, 2012; Khatiwala et al., 2009).

To quantify these dynamics, physical ocean circulation models are used to simulate the movement of water masses based on temperature, salinity, pressure, and density gradients. These models are often coupled with Lagrangian particle-tracking techniques, where virtual tracers (representing parcels of water or dissolved carbon) are followed through the modeled flow fields. Particle tracking allows to estimate not only the residence time of DIC in deep waters but also its pathways and probability of re-exposure to the surface ocean. These tools identify if and where deep ocean conditions support durable carbon removal and sequestration.

For example, Southern Ocean circulation patterns indicate that deep water in the South Pacific Ocean at a latitude of ~45-50°S will flow northward as part of Antarctic Bottom Water (AABW; Solodoch et al., 2022) in the Deep Western Boundary Current which can upwell ~350 years later in the North Pacific Ocean depending on sequestration site (Matsumoto, 2007).

[3] While a fraction of the carbon deposited into the deep sea will be incorporated into the sediments, there is no reliable method to accurately determine the fraction for the purposes of quantifying net carbon removal. Therefore, for the purposes of quantifying the stored carbon (see section 6), 100% of the carbon that reaches the seafloor is assumed to remineralize in the deep sea waters and remain in the deep sea circulation. However, for assessing potential environmental impacts (see section 4) the fraction of carbon, or any decomposition products, which are incorporated into the sediment are considered when assessing potential risks and impacts to the benthic ecosystems.

2. Point of creation of the CO_2 Removal Certificate (CORC)

2.1. The CO_2 Removal Supplier

2.1.1. The CO_2 Removal Supplier is the party authorized to represent the participants necessary to perform the end-to-end activities associated with an MCFS activity seeking certification under this methodology (see also section 3.3). Examples of entities which could be identified as the CO_2 Removal Supplier include but are not limited to the following:

- The operator of the Substrate deployment system.
- The owner of the Substrate deployment system.
- The owner of the stored CO_2.

In particular, the CO_2 Removal Supplier does not need to be the operator of the process creating the CO_2 to be stored (e.g. operating the deployment of the Substrate).

2.1.2. The CO_2 Removal Supplier is responsible for making end-to-end data available and accessible for 3rd party verification. This includes delivering data needed to assess the eligibility of the activities, quantify the predicted net carbon removal, and monitor the necessary parameters at the storage site after Substrate deployment (see also section 9).

2.2. Production facility

2.2.1. The production facility is the ensemble of physical assets necessary to perform the end-to-end activities associated with a MCFS activity, and subject to the Production Facility Audit as per the terminology defined in the Puro Standard General Rules.[4] For the purposes of this methodology, a Production Facility comprises one or several Substrate production sites, a logistic chain for Substrate transport, infrastructure for Substrate processing, and an Area of Interest[5], which may include one or several deployment and sinking sites within the activity boundary (figure 2.1), as further detailed in subrules a-c.

a. The Area of Interest registered under the Production Facility shall be located in a single jurisdiction and operational at the time of the Facility Audit. The Area of Interest shall have broadly consistent:

[4] Available in the Puro Standard document library.

[5] An Area of Interest is defined as the geographical area permitted for the MCFS activity as further defined in rule 3.2.3 and rule 3.7.1.

- Climatic conditions.
- Oceanographic conditions.
- Risk profile related to storage efficiency and environmental safety.

b. Any change in the definition of the Production Facility requested by the CO_2 Removal Supplier during the Crediting Period will require an update of the Production Facility definition (see also rule 2.2.2b).

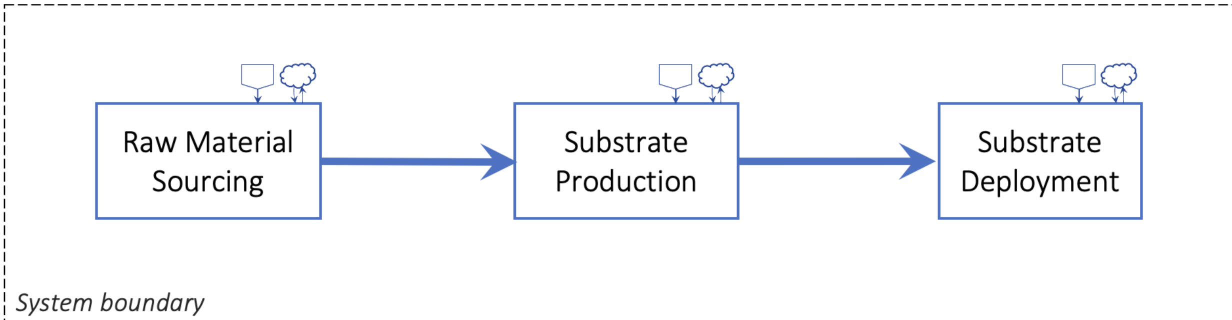

Figure 2.1. Activity boundary in the context of a Microalgae Carbon Fixation and Sinking approach. Note, that transportation of the Substrate occurs between the stages of the activity. More detailed requirements for the activity boundary are found in section 7.2.

2.2.2. A Production Facility and the associated activity is determined as eligible for issuance of CO_2 Removal Certificates (CORCs) once the Production Facility has undergone a third-party verification by a duly appointed Auditor performing a Facility Audit.

a. The Production Facility Auditor verifies the Production Facility conformity to the requirements for activities under this methodology, and the proofs and evidence needed from the CO_2 Removal Supplier.

b. The CO_2 Removal Supplier may include within the Production Facility additional storage sites conforming to rule 2.2.1 without having to undergo a new Production Facility Audit, provided that such additions comply with the requirements for eligible Area of Interest and Substrate deployment and sinking site (section 3.7), and are approved by the Issuing Body and verified during an Output Audit.

2.2.3. The Production Facility Auditor collects and checks the standing data of the CO_2 Removal Supplier and the Production Facility, which includes:

- A certified trade registry extract or similar official document stating that the CO_2 Removal Supplier's organization legitimately exists.

- The CO_2 Removal Supplier registering the Production Facility in the Puro Registry.
- Locations of the storage site(s) forming the Production Facility.
- Whether the Production Facility has benefited from public financial support.
- Date on which the Production Facility becomes eligible to issue CORCs.

2.2.4. The Crediting Period in this methodology is 5 years starting from the first date of the first monitoring period (see rule 5.2.1). The Crediting Period may be renewed twice by successfully undergoing a new Production Facility Audit. The Crediting Period shall not overlap with another Crediting Period.

2.3. Point of creation

2.3.1. The point of creation of the CO_2 Removal Certificates (CORCs) is defined as the earliest point in the CO_2 Removal process when the CORCs can be claimed. For this methodology, the point of creation of the CORC is the moment when the project's inputs, namely the Substrate and the attached biomass, is assessed to have reached the seabed sediment in a manner that prevents re-emissions of GHGs to the atmosphere during the course of an eligible activity, and the data records thereof can be verified.[6]

[6] Time of deployment is here defined as the point when a complete data trail is available for verification of the end-to-end quantities of carbon sourced and stored.

3. Eligibility requirements

3.1. Overall principles

In broad terms, an eligible activity is capable of safely and durably storing CO_2 captured by phytoplankton photosynthesis. In practice, the CO_2 removal is achieved by growing additional phytoplankton, of local species, on engineered Substrates, and subsequently sinking them into the deep ocean waters and sediment (figure 3.1).

It is important that the requirements for MCFS activities ensure durable, robustly quantifiable CO_2 removal, conducted in a manner which leads to no net harm[7] to the environment (e.g. loss of biodiversity, disruption of marine food webs), or to society (e.g. through economical losses due to disruption of fishing activities or unjust use of economic resources).

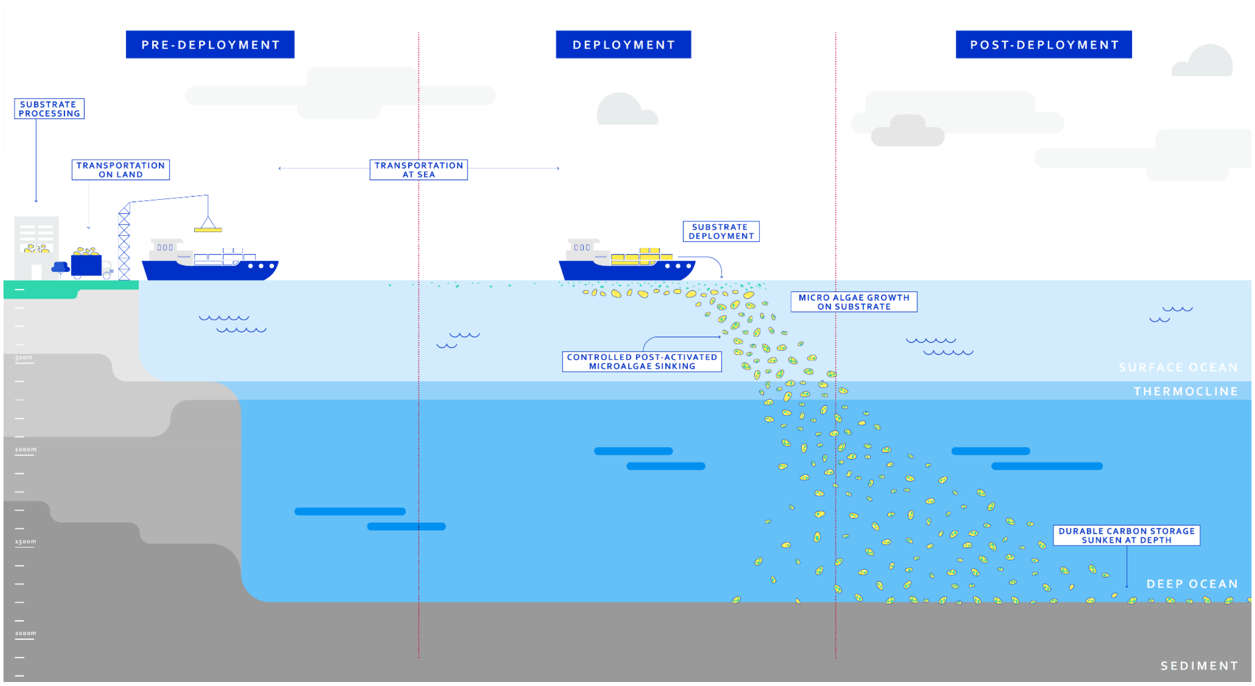

Figure 3.1. A schematic example of a CO_2 removal activity within the scope of this methodology.

While MCFS is a novel approach to remove and sequester CO_2, some external frameworks, regulations, acts, laws, protocols and conventions, cover parts of the MCFS activity. The below-

[7] While the MCFS activity has significant potential to help mitigate the global effects of climate change, it is paramount that the sourcing, production, deployment and storage activities are conducted in a manner such that the benefits significantly outweigh the disadvantages.

listed examples of such resources contain useful information, outlines and recommendations on eligible activities, risk assessment, monitoring and other practicalities. Please note, that the following list is not exhaustive, and contains international agreements which have not yet been ratified, while they may have been recognized as binding agreements in certain jurisdictions.

- International
  - The Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matters, 1972 (The London Convention)
  - The London Protocol, 1996
    - Guidance for Consideration of Marine Geoengineering Activities.
    - Resolution LP.4(8) On the Amendment to the London Protocol to Regulate the Placement of Matter for Ocean Fertilization and Other Marine Geoengineering Activities
  - The United Nations Convention on the Law of the Sea (UNCLOS)
  - International Convention for the Prevention of Pollution from Ships (MARPOL)
    - Annex I Regulations for the Prevention of Pollution by Oil (1983)
    - Annex II Regulations for the Control of Pollution by Noxious Liquid Substances in Bulk (1987)
    - Annex III Prevention of Pollution by Harmful Substances Carried by Sea in Packaged Form (1992)
    - Annex IV Prevention of Pollution by Sewage from Ships (2003)
    - Annex V Prevention of Pollution by Garbage from Ships (1988)
    - Annex VI Prevention of Air Pollution from Ships (2005)
  - Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention)
- The United States
  - The Marine Protection, Research and Sanctuaries Act (MPRSA)
  - Environmental Protection Agency's regulations for implementing the MPRSA: 40 Code of Federal Regulations (CFR) 220-229
  - National Marine Carbon Dioxide Removal Research Strategy
  - Clean Water Act, Section 402: National Pollutant Discharge Elimination System
- European Union

- Directive 2008/56/EC of the European Parliament and of the Council (Marine Strategy Framework Directive (MSFD))
- Directive 2017/845/EC, amending Directive 2008/56/EC of the European Parliament and of the Council as regards the indicative list of elements to be taken into account for the preparation of marine strategies

While adherence to the above-listed external documents is not required in this methodology (except if/when explicitly stated in a numbered rule, or required by local regulations), they can be a useful source of background information to assist the CO_2 Removal Supplier in creating a well designed and monitored MCFS project. The CO_2 Removal Supplier may also use other applicable guidance documents than those listed.

3.2. Requirements for general eligibility

3.2.1. An eligible activity is an activity capable of fixation of CO_2 in the form of organic carbon, followed by long-term storage in the deep ocean and / or in ocean sediments in the form of organic or inorganic carbon. This is done via the addition of eligible Substrate material that increases both the rate of carbon fixation and the rate of organic carbon sinking in the ocean, inhibiting carbon to be released back into the atmosphere for at least 200 years (see section 3.6).

3.2.2. The CO_2 Removal Supplier shall demonstrate that the Substrate is sourced and manufactured in accordance with any applicable local, regional, national or international regulations.

3.2.3. The CO_2 Removal Supplier shall obtain all necessary permits or authorizations to conduct Substrate deployment operations prior to introducing Substrate to the deployment site. All deployment sites shall be approved by the competent local authority or regulatory body and hold relevant permits or authorizations for all activities within the Activity Boundary.

3.2.4. The project activity shall take place in oceanic regions that 1) facilitate carbon removal through sufficient air-sea gas exchange following phytoplankton growth, and 2) facilitate durable storage of that carbon in the deep ocean and/or sediments through physical and chemical conditions that prevent emission back to the atmosphere for at least 200 years.

3.2.5. All installations and operations relating to the MCFS activity shall comply with all local, regional, national or international laws, regulations, and other statutory requirements (including, but not limited to requirements for deployment and sinking site characterization, deployment operations, monitoring and reporting, as well as environmental, ecological, and social requirements) applicable for the deployment site.

3.2.6. The deployment of Substrate into an applicable deployment site shall only take place either within a sovereign state's Exclusive Economic Zone (EEZ) as determined in the United Nations Convention on the Law of the Sea (UNCLOS) Part V[8], or Extended Continental Shelf (ECS) as defined in UNCLOS Part IV[9] and Annex II[10] as further detailed in subrules a-c.

a. The EEZ or ECS, or any sector of it, shall not be a subject of a dispute between sovereign states.

b. In cases where the limits of the ECS have not been established based on the recommendations of the Commission on the Limits of the Continental Shelf[11], operations shall be restricted to the EEZ.

c. Additionally, the CO_2 Removal Supplier shall follow any further restrictions on operations within the EEZ or ECS, set by the applicable local, regional, national or international regulations and legislations.

3.2.7. The CO_2 Removal Supplier shall demonstrate that the project activity takes place in an area where it will not interfere with sensitive ecosystems and with activities described by the relevant jurisdiction as indigenous rights, complying with the Puro Standard General Rules[12] and other Standard Requirements[13]

3.2.8. All facilities and equipment used for Substrate sourcing, processing, transport, and deployment shall be constructed or installed according to national best practices and in compliance with statutory requirements. All installations shall be approved by local authorities and hold relevant permits for their operation. Some examples of such facilities and equipment include warehouses and facilities for manufacturing or storing the Substrate.

3.2.9. The CO_2 Removal Supplier may utilize shared infrastructure for Substrate sourcing, processing, transport, or deployment. Shared infrastructure may be utilized even if such infrastructure is also utilized for non-eligible activities, such as port infrastructure.

3.2.10. The CO_2 Removal Supplier shall demonstrate the baseline carbon removal scenario for their intended MCFS approach. The baseline is a conservative scenario of what likely would

[8] United Nations Convention on the Law of the Sea, Part V, Exclusive Economic Zone

[9] United Nations Convention on the Law of the Sea, Part IV, Continental Shelf

[10] United Nations Convention on the Law of the Sea, Annex II. Commission on the Limits of the Continental Shelf

[11] United Nations Commission on the Limits of the Continental Shelf (CLCS)

[12] Available in the Puro Standard document library.

[13] Ibid.

have happened without the MCFS activity. For more requirements on the baseline determination, see section 6.2.

3.3. Requirements for the CO_2 Removal Supplier

The activities associated with a particular MCFS project can involve multiple site operators collaborating within the project boundary. While the CO_2 Removal Supplier can act as the Substrate sourcing operator, logistics operator and the deployment operator, the responsibility of these operations may also be transferred to external operators (see rule 3.3.2) by contractual agreements.

3.3.1. The CO_2 Removal Supplier shall provide a certified trade registry extract or similar official document stating that it is validly existing and in compliance with the legislation of the host jurisdiction.

3.3.2. The CO_2 Removal Supplier shall clearly establish and demonstrate the ownership of the CO_2 Removal project through either proof of direct ownership, or through contracts with external operators[14] where relevant. The CO_2 Removal Supplier shall furthermore prove with contracts or authorization documents its sole ownership of the durably stored carbon.

3.3.3. The CO_2 Removal Supplier shall provide, where applicable, evidence of valid permits, authorizations, licenses, or other equivalent regulatory control documents to operate any industrial facilities within the activity boundary. The CO_2 Removal Supplier shall furthermore provide evidence of possessing the rights to allow for appropriate monitoring at any stage within the activity boundary.

3.3.4. Where any part of the MCFS activity is contracted to an external operator, the CO_2 Removal Supplier shall establish a clear division of responsibilities and liabilities between the CO_2 Removal Supplier and the external operator, which shall at least address:

- Conducting the required monitoring activities, such as measuring device set-up, maintenance, and the monitoring of individual parameters.
- Preventive and corrective measures taken in case of a reversal or re-emission.
- Post-deployment and site closure requirements and expenses until the transfer of responsibility.

3.3.5. When any part of the MCFS activity is contracted to an external operator, the CO_2 Removal Supplier shall provide the contractual information necessary for assessing compliance with

[14] For the purposes of this methodology, an external operator is defined as any party (such as the operator of the substrate sourcing and processing, the operator of the substrate deployment system or the logistics operators) operating on behalf and at the direction of the CO_2 Removal Supplier for provision of services relating to the MCFS activity.

this methodology, the Puro Standard General Rules[15] and other Standard Requirements[16], as well as any applicable local laws, regulations, or other binding obligations. This information shall at least include:

- Certified trade registry extracts or similar official documents stating that any and all external operators are validly existing and in compliance with the legislation of the host jurisdiction.
- Documentation that the CO_2 Removal Supplier is in contractual agreement with the external operator for the purpose of achieving durable CO_2 Removal.
- In the case of an external Substrate deployment operator, documentation establishing that the biomass received by the deployment operator will be deployed and durably stored into an eligible ocean storage site.
- Proof of sole ownership to the Substrate sourced, transported or stored, and attestation of no claim where necessary as per rule 3.5.1.
- Documentation establishing the right to audit the relevant documents and equipment belonging to the external operator for the purposes of CORC Issuance.

3.3.6. The CO_2 Removal Supplier is responsible for ensuring that sufficient data is available and accessible for auditing and verification that the MCFS activity is compliant with the requirements of this methodology and other applicable Puro Standard Requirements[17], as well as any applicable local laws, regulations, and other binding obligations. This includes but is not limited to delivering the necessary data to assess the eligibility of the activities, and quantify the predicted net carbon removal. In particular, the CO_2 Removal Supplier shall provide all calculation functions and parameters utilized for the quantification of net CO_2 Removal in a clear and consistent manner (see section 11).

3.4. Requirements for additionality

3.4.1. To demonstrate additionality, the CO_2 Removal Supplier shall demonstrate that the MCFS activity is not required by existing laws, regulations, or other binding obligations. Further, the CO_2 Removal Supplier shall convincingly demonstrate that the CO_2 removals are a

[15] Available in the Puro Standard document library.

[16] Ibid.

[17] Ibid.

result of carbon finance, as further detailed in the Puro Additionality Assessment Requirements.[18]

3.5. Requirements for prevention of double counting

3.5.1. The CO_2 Removal Supplier shall ensure that the CO_2 removal is not double-counted in a manner which would infringe the Puro Standard General Rules.[19] In particular, the General Rules entail that:

a. The CO_2 Removal Supplier shall evidence that it has the sole right to claim CORCs from the CO_2 placed in storage, and that other parties involved in the supply chain have no such right. This can be evidenced by contracts or attestations exhibiting the relation between the involved parties.

b. The CO_2 Removal Supplier or any party involved in the supply chain shall not associate any CO_2 removal claim (whether a marketing, branding, or footprint claim) to any other products or services delivered by the CO_2 Removal Supplier or involved party (including other types of environmental products, such as renewable energy certificates), unless the issued CORCs have been explicitly retired for this purpose.

c. The CO_2 Removal Supplier or any party involved in the supply chain may still report their direct emissions and removals in other sectoral GHG inventories (e.g. mandatory national reporting for UNFCCC, or voluntary corporate reporting), making adequate disclosures regarding the issuance of CORCs.

3.5.2. The CO_2 Removal Supplier shall determine if CORCs are required for other international mitigation purposes such as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), or other entities operating in the voluntary carbon market. To this end, the CO_2 Removal Supplier shall follow the Puro Standard Article 6 Procedures[20] to ensure proper reporting of the issuance, transfer, and retirement of CORCs, and to avoid double counting.

[18] Available in the Puro Standard document library.

[19] Ibid.

[20] Ibid.

3.6. Requirements for the substrate

3.6.1. The CO_2 Removal Supplier shall use Substrate(s) that ensure an efficient process of carbon fixation and export, while minimizing any possible harm to any oceanic ecological system. The eligible components of the Substrate may include one or several of the following:

a. Non-toxic and non-hazardous organic material.

b. Non-toxic and non-hazardous inorganic material, such as minerals.

c. Trace elements up to 0.5 % of the total mass of the Substrate.

The CO_2 Removal Supplier shall provide a detailed characterization of the Substrate, pending approval by the Issuing Body.

3.6.2. The CO_2 Removal Supplier shall demonstrate that all of the Substrates (>99 w/w%) deployed for each batch fulfills the following criteria:

a. The range of diameters or geometrical face of each individual Substrate unit shall be between 0.5 mm and 20 mm. The 3D geometrical structure is not limited, and any geometrical structure can be used (e.g., sphere, rectangular, cube).

b. The density of the solids that compose the pristine substrate shall be at minimum 0.01 g/cm^3 higher than the density of the water at the deployment site.

c. The overall density of the substrate during the sinking phase (or during the transition between fixation and sinking phases) shall be at minimum 0.01 g/cm^3 higher than the density of the water at the sinking site.

d. The Substrate shall have a mechanism for containment of the phytoplankton, in a manner that minimizes the loss of accumulated phytoplankton and adjacent bacteria (fixed carbon) due to physical forces.

e. The trace elements included shall be contained within the Substrate, minimizing nutrient leaching into the surrounding waters (see rule 9.4.12).

3.6.3. The CO_2 Removal Supplier shall ensure and demonstrate that the Substrate includes an autonomous or controlled **sinking** mechanism, to avoid extended floating periods and enhance the export efficiency, as defined in subrules a-b.

a. The maximum floatation period (fixation phase; see rule 9.6.1. b) shall not exceed 30 days.

b. The sinking velocity of the Substrate shall be at minimum 20 m/h.

The CO_2 Removal Supplier shall determine the specific fixation phase length and sinking velocity of the Substrate for each deployment in the Monitoring Plan, which shall be made available to the Auditor.

3.6.4. Prior to deployment, the CO_2 Removal Supplier shall assess the quality and variability of a representative sample of each deployment batch of the Substrates, including at least:

a. Mass per unit of Substrate.

b. Volume per unit of Substrate.

c. Mass fraction (%) of carbon per unit of Substrate (%C/unit) and total volatile solids (organic matter) (%TVS/unit) (rule 9.3.3.).

d. Mass fraction (%) of the Substrate unit remaining after a floatation period of 30 days in oceanic conditions as determined in rule 9.4.3.

e. Floating time (days), which shall not exceed the maximum floating period (see rule 3.6.3), as further determined in rule 9.4.4 and rule 9.6.15.

f. Sinking rates (m/h), as further determined in rule 9.4.11.

g. Trace elements leaching of the Substrate (rule 9.4.12).

h. Determination of the share of organic carbon of the Substrate material. For further requirements, see section 6.1.

3.6.5. The analyses shall be performed for a statistically representative sample of the entire batch of Substrate deployed, following the requirements determined in subrules a-i.

a. The measurements shall be conducted by using appropriate, peer-reviewed scientific best practices or appropriate standard methods.

b. The measurements shall be conducted in laboratories which shall be accredited by national authorities and comply with international testing standards (e.g. ASTM, ISO, AS, D).

c. All analyses performed prior to deployment shall be performed on pristine Substrates.

d. All analyses performed post-deployment shall be performed on appropriately stored and dried Substrates, to ensure accurate results.

e. All analyses shall be performed on a minimum sample size of 100 Substrate units.

f. At least three replicates are required for each analysis.

g. The results shall be tested and compared with their respective coefficient of variation (CF) values.

h. For the validation process, half or double of the sample size (50 or 200 units) shall be tested for verification of a representative sample size.

i. In case the variability between the replicate analyses for any of the parameters is larger than one standard deviation, the CO_2 Removal Supplier shall increase the sample size until the variability is within accepted limits.

3.6.6. The CO_2 Removal Supplier shall ensure that the Substrate maintains its structural integrity during deployment and sinking, e.g. via shear stress tests, compression stress tests, submersion tests or similar.

3.6.7. The CO_2 Removal Supplier shall provide a detailed characterization of micronutrients included in the Substrate, including at least:

a. Detailed list of the micronutrients added to the Substrate.

b. Concentration of each individual micronutrient added to the Substrate as defined by the final solid/substrate (w/w%) content using trace-elements solid measurement method.

3.6.8. All micronutrients added to the Substrate shall:

a. Be in an oxide form.

b. Have a zero to low tendency to dissolve (oxide forms determined as insoluble under ocean conditions - salinity, pH, temperature (Liu & Millero, 2002)).

3.6.9. Prior to deployment, the CO_2 Removal Supplier shall evidence that the concentrations of potentially toxic elements (PTEs) in the Substrate do not exceed the limits defined in applicable local, regional, national or international legislation. PTEs are defined as specific chemical elements that can be harmful to living organisms, including plants, animals, and humans, when present in sufficient concentrations. If the Substrate may have been exposed to chemicals or other treatments which may pose a risk to aquatic ecosystems, the CO_2 Removal Supplier shall provide a chemical analysis of the possible contaminants of the Substrate to be deployed. To minimize the environmental risks, at least the following parameters shall be analysed:

a. Levels of heavy metals that could leach into the ocean and bioaccumulate in marine organisms, including but not limited to mercury (Hg), lead (Pb), cadmium (Cd), arsenic (As), chromium (Cr), copper (Cu), nickel (Ni), and zinc (Zn). The heavy metal concentrations obtained shall be reported and compared against established regional, national or international safety thresholds.

b. Levels of polycyclic aromatic hydrocarbons (PAHs) shall be analyzed. The contamination levels obtained shall be reported and compared against established regional, national or international safety thresholds.

c. Level of polyfluoroalkyl substances (PFAS) shall be analyzed. The contamination levels obtained shall be reported and compared against established regional, national or international safety thresholds.

d. Levels of pesticides, including organophosphates, neonicotinoids, and herbicides, shall be analyzed when applicable. The contamination levels obtained shall be reported and compared against established regional, national or international safety thresholds.

In case any of the above-mentioned threshold values are exceeded, the Substrate will be considered ineligible.

3.7. Requirements for the Area of Interest and the deployment and sinking site

To ensure the durable storage of the Substrate with fixated carbon, the deployment and storage site must meet several critical requirements. This section provides requirements and prerequisites for assessing the environmental conditions of the deployment and storage site, aiming to ensure its long-term suitability for carbon storage.

3.7.1. The CO_2 Removal Supplier shall maintain precise geographic records of the Area of Interest (AOI) (see rule 2.2.1).

a. The geographic boundaries of the Area of Interest shall be defined and documented as a polygonal perimeter, including latitude and longitude coordinates for all vertices, as well as depth ranges within the area.

b. The Area of Interest boundaries shall be recorded using Global Navigation Satellite System (GNSS) or equivalent geospatial technology, with coordinates expressed in degrees and decimal minutes (DDD° MM.MMM') format and verified for accuracy.

The extent of the Area of Interest shall be determined in the required permits obtained by the CO_2 Removal Supplier (see rule 3.2.3 and rule 3.2.4).

3.7.2. The CO_2 Removal Supplier may have one or several **deployment and sinking site(s)** located within the boundary of the Area of interest. The CO_2 Removal Supplier shall maintain precise geographic records of all Substrate deployment and sinking sites used in the project.

a. The geographic boundaries of a deployment and sinking site shall be defined and documented as a polygonal perimeter, including latitude and longitude coordinates for all vertices, as well as depth ranges within the area.

b. The deployment and sinking site boundaries shall be recorded using Global Navigation Satellite System (GNSS) or equivalent geospatial technology, with coordinates expressed in degrees and decimal minutes (DDD° MM.MMM') format and verified for accuracy.

3.7.3. The CO_2 Removal Supplier shall demonstrate that each deployment and sinking site is located at minimum 12 nautical miles from shoreline, within a sovereign state's EEZ (see rule 3.2.5).

3.7.4. The CO_2 Removal Supplier shall demonstrate that the sinking occurs in a region where deep ocean circulation will maintain that the sunken carbon will remain out of contact with the atmosphere for at least 200 years. The sinking site shall be located within the Area of Interest (see rule 3.7.1).

3.7.5. The CO_2 Removal Supplier shall demonstrate that the project activity takes place in an area characterized as High Nutrient Low Chlorophyll (HNLC) region (Yoon et al., 2018); see section 1.6). The CO_2 Removal Supplier shall demonstrate that the individual nutrient and chlorophyll *a* concentrations comply with the following criteria:

a. Nitrate (NO_3) > 8 μM

b. Phosphate (PO_4) > 0.5 μM

c. Iron (Fe) < 0.2 nM

d. Chl a < 1 μg/L

3.7.6. The CO_2 Removal Supplier shall provide detailed characterization of the atmospheric and oceanographic conditions of the Area of Interest. As evidence, the CO_2 Supplier shall utilize relevant measurements, peer-reviewed scientific literature, databases such as the Copernicus Marine Service[21] or other applicable peer-reviewed scientific data. The data from scientific literature or databases shall in all cases include measured data. The evidence shall be made available for the Auditor and verified during the baseline characterization.

3.7.7. The CO_2 Removal Supplier shall provide a detailed characterization of the seafloor conditions at the Area of Interest (see rule rule 3.7.1). As evidence, the CO_2 Removal Supplier shall provide at least:

[21] E.U. Copernicus Marine Service Information

a. Assessment of seafloor geological stability. The sinking site shall not be located in a region subject to a significant risk of seismic or volcanic activity. This shall be evidenced by providing a geohazard assessment of the geological and geophysical stability of the seabed.

b. Assessment of any benthic ecosystems which may be affected by the activity or any potential decomposition products, such as elevated dissolved organic carbon (DOC) levels, including flora and fauna (see rule 4.4.3). For further requirements on benthic habitat mapping, see rule 3.7.8.

c. Evidence of little to no anthropogenic disturbances. The sinking site shall be located in an area which is not impacted by human activities, such as shipping lanes, fisheries, industrial zones and dredging areas. Similarly, the CO_2 Removal Supplier shall minimize impacts of the MFCS activity on maritime and coastal activities (see section 4.4 for further details).

3.7.8. The CO_2 Removal Supplier shall characterize the range of benthic habitats, identify the occurrence of protected species or sensitive communities, and note any organisms particularly vulnerable to changes in oxygen or particulate smothering within the Area of Interest. The characterization shall be based on a thorough assessment of existing biological datasets, such as macrofauna surveys, photographic and video evidence, as well as physical data from legacy multibeam voyages, existing habitat maps, and heterogeneity models for the Area of Interest. The assessment should also collate historical chemical data, including dissolved oxygen measurements from CTD casts and any available infaunal pore-water analyses.

3.7.9. The CO_2 Removal Supplier shall provide a detailed characterization of the oceanographic conditions of the deployment and sinking site (see rule 3.7.2). The assessment shall be based on data which includes the average of multiple spatial data points at the relevant seasons for at least five consecutive years, collected within the last 10 years, given that the data is accessible. The data shall include the best available spatial resolution consisting of at least 50 depth layers and portray any intra-seasonal variations at minimum on a monthly resolution. As evidence, the CO_2 Removal Supplier shall provide at least:

a. Assessment of monthly averages of physical and chemical water column characteristics, including but not limited to depth, temperature, salinity, dissolved oxygen, macronutrients and micronutrients (N, P, Si, Fe, Mn), carbonate system (DIC, TA and/or pH) data of the full water column at a minimum resolution of data-point per 10,000 km^2, within the AOI.

b. Assessment of horizontal and vertical seawater velocities maps at key depths in the water column (e.g., surface, 100 m, 1000 m, and near the seafloor) using both observational datasets and reanalyzed modeled outputs. The velocity maps shall be supported by in-situ measurements at best available spatial resolution within the AOI.

c. Assessment of the depth and seasonality of the thermocline and the surface mixed layer, derived from both regional climatologies and in-situ profiles taken within the boundary of the AOI.

d. Assessment of the surface water retention time and identification of downwelling regions that may influence the air-sea gas exchange and impact the CO_2 removal efficiency. Instead of the individual deployment and sinking site, the assessment shall be conducted for the extent of the AOI.

e. Assessment of bottom water mass retention time and potential upwelling zones that may affect the durability of carbon storage, using a combination of model data, observational evidence, and global circulation models (see rule 9.4.15). Instead of the individual deployment and sinking site, the assessment shall be conducted for the extent of the AOI.

f. Assessment of any planktonic community and ecosystems, including potential impacts from the project activity or decomposition byproducts, such as elevated dissolved organic carbon (DOC) concentrations. Instead of the individual deployment and sinking site, the assessment may be conducted for the extent of the AOI.

The CO_2 Removal Supplier shall assess and evaluate the above-mentioned characteristics utilizing data produced and distributed by the Copernicus Marine Service[22] or other relevant databases and relevant peer-reviewed scientific literature. When based on information obtained from databases or literature only, the assessment shall always include reanalyzed data based on direct measurements, which may be supplemented with assimilations from satellite observations and processed with numerical models. When possible, the CO_2 Removal Supplier should supplement the data with in-situ measurements. The evidence shall be made available for the Auditor and verified during the baseline characterization.

3.7.10. The CO_2 Removal Supplier shall ensure that the deployment and sinking site is located in an area deep enough for the Substrates to sink beneath the euphotic zone (typically under 200 m) and the upper mixing layer to prevent conditions for photosynthesis and to ensure

[22] E.U. Copernicus Marine Service Information

export below the mixing layer.[23] The appropriate sinking site depth shall be determined by the CO_2 Removal Supplier, on a case-by-case basis, taking into account the oceanographical conditions, factoring in the stratification and seasonal variability of the water masses (rule 3.7.9) at a specific deployment and sinking site. The CO_2 Removal Supplier shall determine:

a. The total water depth at the sinking site.

b. The depth of the euphotic zone shall be determined as the depth where the surface photosynthetically available radiance (PAR) is attenuated to 0.5% (Wu et al., 2021). The depth of 0.5% surface PAR shall be determined based on the diffuse attenuation coefficient of PAR (K_d) from measurements of downward irradiance across the solar radiation spectrum (400-700 nm) taken at least at two depths: just below the ocean surface and within the top 50-100 m. The 0.5% PAR depth shall be calculated following the methods described in (Marra et al., 2014).

The sinking site depth shall be approved by the Issuing Body.

3.7.11. The CO_2 Removal Supplier shall demonstrate that the project activity takes place in an area where ocean circulation patterns enable the carbon-depleted surface waters to remain at the surface and in contact with the atmosphere for long enough to allow for ample air-sea gas exchange prior to downwelling of the surface water masses. Further requirements for the assessment of air-sea gas exchange efficiency and quantification are described in rule 6.1.9.

3.7.12. The CO_2 Removal Supplier shall demonstrate that the project activity takes place in an area where the oceanographic and seafloor conditions ensure long-term carbon sequestration of at least 200 years by applying a physical oceanographical model, as further detailed in section 9.5. The CO_2 Removal Supplier shall furthermore explicitly determine the depth at which the water mass will remain in the deep oceans for a period of at least 200 years (z_{stored}, in meters below sealevel, see also rule 6.1.7).

3.7.13. Prior to deployment, the CO_2 Removal Supplier shall establish a control site. The control site shall serve as the benchmark for the environmental impact assessment detailed in section 4.5. The control site shall be geographically proximate to the deployment and sinking site, yet it must remain unaffected by substrate disturbances, and the specific location shall be determined based on the estimated substrate trajectories (rule 9.5.15) to

[23] This methodology does not strictly require a specific minimum sinking depth as the required minimum sinking depth varies based on the sinking site location, local oceanographic conditions and global ocean circulation patterns. However, deeper sites are generally more suitable for durable carbon storage. The eligibility of each individual sinking site proposal is carefully assessed based on detailed characterization, following the requirements set in this methodology.

confirm it lies outside the anticipated impact area of the deployment and sinking operations.

3.7.14. The CO_2 Removal Supplier shall stimulate productivity of local phytoplankton. The use of any phytoplankton seeding for seeding the growth is considered ineligible.

3.7.15. The CO_2 Removal Supplier shall increase the carbon fixation above the local baseline (see section 6.2) by increasing the growth of local phytoplankton. This shall be achieved through the addition of micronutrients that are otherwise limiting.

3.7.16. The export of carbon to the deep sea shall be intentional and exceed the natural export efficiency to the sediment (~1%; (Middelburg, 2019). The project activity shall increase the export efficiency of the local phytoplankton above either

a. The local baseline (Nelson et al., 2002; Pollard et al., 2009; Smith et al., 2018), or

b. The global baseline (Ducklow et al., 2001), whichever is higher.

For further details, see section 6.2 for quantification of baseline carbon removal.

3.8. Requirements for the deployment, fixation and export phases

3.8.1. Prior to deployment, the CO_2 Removal Supplier shall assess the estimated duration of the fixation and export phases, which shall be determined as follows:

a. Fixation phase (Floatation): Duration of the period when the Substrate floats on the surface ocean.

b. Export phase (Sinking): Duration of the period when the Substrate sinks to the seafloor.

The duration of each phase shall be evaluated based on quality and variability tests of the Substrate prior to deployment (rule 3.6.4). The estimated durations of each period shall be validated during the field monitoring operations (section 9.6).

3.8.2. Prior to deployment, the CO_2 Removal Supplier shall determine the estimated trajectory and dispersal of the Substrates. The estimation shall be specific to each deployment and sinking site, and shall be conducted using a modeling approach following requirements determined in subrules a-e.

a. The trajectory and dispersion of the Substrate shall be simulated using a Lagrangian model, including a particle release simulation based on the total mass of Substrate deployed (see section 9.5).

b. The model shall incorporate intra-seasonal variability of the oceanographic conditions, to ensure that the Substrate trajectory and dispersal estimates reflect realistic environmental dynamics at the deployment and sinking site.

c. The model shall integrate historical reanalysis (hindcasts) and simulated forecasts of physical models utilized by the Lagrangian model.

d. A minimum of 10-year hindcast data shall be incorporated into the model a range of plausible trajectories and dispersal scenarios under variable oceanic conditions.

e. The model-based estimation of the Substrate trajectory and dispersal shall be validated using in-situ monitoring data collected during deployment operations, as further detailed in section 9.4. This validation shall confirm model reliability and improve confidence in trajectory predictions.

3.8.3. The CO_2 Removal Supplier shall evaluate the dispersion of Substrates using a particle tracking oceanographic model. The evaluation shall be developed individually for each deployment, and shall account for the total mass of Substrates deployed. The model inputs shall reflect the deployment-specific fixation phase length and sinking velocity of the Substrate (rule 3.6.3.), which shall be validated by Substrate characterization (rule 3.6.4). Model outputs shall include the spatial trajectories and calculated Substrate concentrations both at the end of the fixation phase and upon reaching the seafloor. Simulations shall also quantify the dispersion characteristics of the Substrate plume at the seafloor, including the mean, median, minimum and maximum concentrations. The model result shall be validated during the field operations, as further defined in section 9.6.

3.8.4. The CO_2 Removal Supplier shall use a pulsed deployment approach using a Nutrient–Phytoplankton–Zooplankton–Detritus (NPZD) framework (see rule 9.5.17). The NPZD framework shall be used to maximise net carbon fixation efficiency by reducing losses caused by grazing and remineralization, and shall facilitate rapid seawater replenishment following the sinking of the substrate.

3.8.5. The CO_2 Removal Supplier shall ensure that the sinking rate is fast enough to minimize the contact time with the surface mixed layer, following the requirements set in rule 3.6.3 and 9.6.15.

3.8.6. The CO_2 Removal Supplier shall provide evidence that the sinking efficiency increases as compared to the baseline sinking efficiency within the area of interest.

3.8.7. The CO_2 Removal Supplier shall maintain precise geographic records of all Substrate deployment and sinking sites used in the project (see rule 3.7.2). The CO_2 Removal Supplier shall keep time stamped records of Substrate deployment, including:

a. The exact dates of each Substrate deployment. Each deployment event, including the trajectory during the fixation phase and the final sinking location, shall be determined and linked to its specific location within the Area of Interest.

b. Exact location, boundary and timeline records of each deployment event, which shall be securely archived and readily available for compliance, monitoring, reporting or verification purposes. Any changes to the deployment and sinking site locations or deployment schedules shall be reported to the Issuing Body and documented properly.

3.9. Requirements for positive sustainable development goal impacts

Please note that the Puro Standard General Rules and the associated Sustainable Development Goals (SDG) Assessment Requirements[24] contain the general requirements related to describing and evidencing positive impacts on SDGs[25] that apply to all methodologies. For example, in the context of MCFS, positive SDG impacts might be related to targets such as reduction of waste through recycling and reuse (SDG 12.5) which may be achieved by sustainable sourcing and circular design; minimization of ocean acidification (SDG 14.3); and development of opportunities for decent work and economic growth (SDG 8) by creating new jobs in, and related to MCFS projects, across various skills and professions.[26]

3.1.1. The CO_2 Removal Supplier shall provide descriptions, evidence, and information on the positive impacts of the MCFS on SDGs in accordance with the Puro Standard General Rules and other Standard Requirements (in particular, the SDG Assessment Requirements). Specifically, the Puro Standard General Rules entail that:

a. The CO_2 Removal Supplier shall provide qualitative descriptions of expected positive impacts on Sustainable Development Goals (SDGs) before the Production Facility Audit.

b. The CO_2 Removal Supplier shall provide qualitative and quantitative evidence of positive impacts on SDGs for the Output Audit based on the SDG Assessment Requirements provided by the Issuing Body.

[24] Available in the Puro Standard document library.

[25] Resolution adopted by the General Assembly on Work of the Statistical Commission pertaining to the 2030 Agenda for Sustainable Development, G.A. Res 78/206, U.N. Doc. A/RES/71/313 (Jul. 6, 2017). Note that this original SDG indicator framework is subject to regular updates, and has since been revised several times.

[26] For a list of currently up to date SDG targets, see the current official SDG indicator list hosted at the United Nations Statistics Division website. Furthermore, the United Nations Department of Economic and Social Affairs website provides a browsable SDG indicator list.

c. The CO_2 Removal Supplier shall, where feasible, provide information on how the MCFS activity is consistent with the relevant SDG objectives of the host country.

4. Reversal, environmental and social risks

4.1. Overview

The primary objective of identifying risks is to detect early and ongoing events and ambiguities that could affect the predetermined objectives of the MCFS activity. Several risks concerning various mCDR approaches have been identified, concerning climate, ecosystems, human health and the lack of adequate regulatory frameworks (Cooley et al., 2023; Keating-Bitonti et al., 2025; Levin et al., 2023; Schenuit et al., 2023). While the scope of this methodology eliminates and limits some of these risks, the MCFS approach has its own specific risks which need to be identified, accounted for and mitigated. These risks can be categorised into **reversal** risks, **environmental** risks and **social** risks.

In the context of this methodology, *risk* refers to events and situations, whose outcomes are (reasonably well) known in advance and needs to be distinguished from *uncertainty*, which refers to aspects of decision-making which are not easily quantified ((Park & Shapira, 2018). The overall risk of an event or situation is often defined as the combination of two parameters: the probability (likelihood) for the event to be realized, and the severity of the event, if realized. Effectively, risk management is composed of four main steps: identification, evaluation, mitigation and control of hazards that could occur within the project boundary. Therefore, an effective risk assessment takes into account the nature and magnitude of risks in relation to the outcome.

For the purposes of this methodology, the term **reversal** refers to an event which cancels, entirely or in part, the effects of an issued CORC (for further details, see the Puro Standard General Rules[27]). Reversals are therefore considered as unaccounted-for events resulting in a situation where at least a part of the removed, quantified and certified carbon represented as a CORC is either released back into the atmosphere (re-emission) or can no longer be considered safely and durably stored for a long term. It is separated from carbon losses (see section 6.3), which include re-emission pathways identified prior to the CORC issuance, and therefore accounted for in the CORC quantification (see rule 5.2.1).

An eligible MCFS activity must also take into consideration multiple **environmental and social risks**, which may negatively impact the terrestrial or marine ecosystems, human health or the local communities. This section outlines the overall criteria to assess, evaluate and mitigate such risks, including certain predetermined risks which all projects seeking for CORC issuance must account for. In addition to the requirements set in the Puro Standard General Rules[28] and in this section of

[27] Available in the Puro Standard document library.

[28] Ibid.

the methodology, further requirements and guidelines are also found in the Puro Stakeholder Engagement Requirements[29], the Puro Stakeholder Engagement Report Template[30] and the Puro Environmental and Social Safeguards Questionnaire[31].

This methodology, together with applicable local legislation and regulations, sets guidelines and rules to mitigate the possible risks and ensure that carbon is safely retained in the selected ocean storage site. Appropriate and transparent collection of data as well as regularly updated monitoring plans are key factors in managing and mitigating risks, but effective risk mitigation also requires efficient and transparent communication and collaboration between the CO_2 Removal Supplier and the local authorities and stakeholders.

4.2. General requirements for risk assessment and management

This section focuses on general risk management criteria applicable for reversal risks as well as environmental and social risks. Further assessment criteria specific to each risk type is defined in the following sections:

- Reversal risks (see section 4.3)
- Environmental and social risks (see section 4.4 and section 4.5).

For all types of risk associated with the MCFS activity, identifying the key risks is the first step towards a design of an effective monitoring, mitigation and response measures to minimize their likelihood and impact. By proactively managing these risks, the CO_2 Removal Supplier ensures the integrity and safety of the operations.

Risks can be proactively managed by utilizing a mitigation hierarchy framework, which aims to efficiently limit the negative impacts or outcomes of a given risk. Such a hierarchy is based on a sequence of five iterative actions (figure 4.1): anticipating the potential risk, avoiding the risk, minimizing and/or mitigating any negative impacts of the risk, and finally, compensating for any residual impacts. The steps are further characterised as:

- Anticipation: The first step comprises identifying potential risks relevant for a specific MCFS activity before they materialize and designing strategies to either avoid, mitigate or minimize their impact.
- Avoidance: Includes measures taken to avoid any negative impacts identified for a given risk. Avoidance measures may include, but are not limited to a careful selection of Substrates (see

[29] Available in the Puro Standard document library.

[30] Available in the Puro Standard document library.

[31] Ibid.

section 3.6) or the deployment and sinking sites (see section 3.7). Effective avoidance measures must be considered during the early stages of the project.

- Minimization: Includes measures to either reduce the duration, intensity or extent of a given risk, in case it cannot be fully avoided. Effective minimization measures may eliminate some negative impacts, if such measures are planned and executed accordingly.
- Mitigation: Includes measures to mitigate the impacts of a given risk, in case the impacts cannot be fully avoided or minimized. Collectively, avoidance, minimisation and mitigation measures serve to reduce, as much as possible, any negative residual impacts of a given risk.
- Compensation: As the last step, compensation measures are the last resort in case avoidance, minimisation and/or mitigation measures are not capable of fully preventing the negative impacts of a given risk. In the context of this methodology, this applies in the case of a reversal event.

Figure 4.1. Mitigation hierarchy framework for risk assessment in the context of MCFS approach.

Note that the Puro Standard General Rules contain requirements on risk assessment and management, particularly in the context of permanence and reversal.

4.2.1. The CO_2 Removal Supplier shall undertake a comprehensive baseline risk assessment prior to project initiation, based on the following criteria:

a. The scope of the assessment shall cover all stages (Substrate sourcing, processing, transportation, deployment and sinking) within the activity boundary (see rule 7.2.4).

b. The assessment shall be systematic and based on robust, science-based risk assessment criteria, against which the significance of a specific risk/impact is evaluated and measured against.

c. The assessment shall comply with the requirements of this methodology, the Puro Standard General Rules[32] and other Puro Standard Requirements[33], as well as any applicable local laws, regulations, and other binding obligations.

4.2.2. The risk assessment criteria shall include at least the following components:

a. Identification and description of the anticipated risk and its impact, including but not limited to the predetermined risks set in this methodology (see section 4.5).

- The impacts may include direct, indirect or cumulative risks.
- The impacts may be either discrete, i.e. isolated events with a clear trigger or a cause, or progressive, i.e. gradual changes that accumulate over time, leading to negative impacts.
- The potential risks include, but are not limited to risks related to geological instability, oceanographic variability, microbial activity, and anthropogenic disturbances.

b. Analysis and estimation of each identified negative impact a specific risk may have, including the characterization of likelihood and severity, assessing the significance of the risk to the CO_2 Removal Project. The CO_2 Removal Supplier shall use the risk matrix presented in table 4.1 to analyse each risk.

- The CO_2 Removal Supplier may suggest using another quantitative and/or qualitative risk scoring system, pending approval by the Issuing Body.

c. Assessment of each identified risk, including acceptable, alert and threshold values for each measurable parameter. The CO_2 Removal Supplier shall further design and implement operating procedures in case the alert or threshold value is reached. The values shall be derived from applicable local regulations or, if no such regulations exist, from other relevant sources, such as peer-reviewed

[32] Available in the Puro Standard document library.

[33] Ibid.

scientific literature or industry best practices. The values shall be periodically reviewed to ensure the safety of the operations.

d. Description of the measures to avoid, minimize, mitigate or compensate the negative impacts of identified risks based on the mitigation hierarchy (figure 4.1), including where relevant a description of the parameters and methods utilized to monitor the potential impacts.

- Preventive and corrective measures shall be identified or planned as contingency measures to reduce risks.
- The risk mitigation strategy may include, but is not limited to, data collected from both in-situ sampling and laboratory experiments conducted by the CO_2 Removal Supplier (see section 9.4).
- When the severity or the likelihood of the risk are at an undesirable or intolerable level (table 4.1), the CO_2 Removal Supplier shall either eliminate or reduce the risk to a safe and acceptable level.
- When the severity or the likelihood of the risk are at an inoperable level (table 4.1), the CO_2 Removal Supplier shall immediately cease all operations, prevent further negative impacts from occurring, and notify the Issuing Body.

e. Description of public participation and consultation, as described in the Puro Standard General Rules[34] and the Puro Stakeholder Engagement Requirements.[35]

[34] Available in the Puro Standard document library.

[35] Ibid.

Table 4.1. A 5x5 risk matrix and descriptions of the risk scores and required actions for the given risk levels.

Risk score	**Risk level**	**Action**
20—25	Inoperable	Critical failure. Requires an immediate seizure of operations. Further avoidance, minimization or mitigation measures are required for the operations to continue.
10–19	Intolerable	High likelihood or severe negative impacts. Requires immediate action to avoid, minimize or mitigate the impacts.
4–9	Undesirable	Manageable risks, which require an active, planned approach for risk avoidance, minimization and mitigation to reduce the negative impacts.
2–3	Acceptable	Minor risks with limited negative impacts. No requirement of immediate action, but effective monitoring and controls are necessary.
1	Negligible	Insignificant risk with negligible consequences. No requirement for immediate action, but requires to avoid future events.

Likelihood → Severity ↓	Very Low (1)	Low (2)	Medium (3)	High (4)	Very High (5)
Minor (1)	1	2	3	4	5
Serious (2)	2	4	6	8	10
Major (3)	3	6	9	12	15
Severe (4)	4	8	12	16	20

Extreme (5)	5	10	15	20	25

4.2.3. The risk assessment shall, to the extent possible, be based on the actual project data acquired during the MCFS activity. The risk assessment, including a review of appropriate preventive and corrective safeguards, shall be reviewed and updated periodically together with the Monitoring Plan (see section 9.2). The assessment shall be made available to the Auditor.

4.2.4. To address the above components partly or in full, the CO_2 Removal Supplier may utilize and refer to other documents (e.g. project description documents, stakeholder engagement reports, or legally mandated environmental and social impact assessment documents) containing the required information, provided that such additional documents are also included.

4.2.5. The CO_2 Removal Supplier shall record and disclose to the Issuing Body any negative environmental or social impacts or reversal events (or claims thereof) occurred during the monitoring period, including but not limited to any legal actions and/or other written complaints filed by affected parties.

4.3. Requirements for reversal risk assessment and management

The long-term success of a MCFS approach ultimately depends on the ability to safely and durably transport carbon in the deep ocean with at least a 200-year storage capability. In this context, a reversal risk is defined as any event or condition that may compromise the storage of carbon in the deep ocean, resulting in the re-emission of the stored carbon back into the atmosphere. More specifically, in the context of this methodology, the durable storage is considered breached if the carbon stock is released back into the surface ocean. Please note, that reversal risks are separate from carbon losses (see section 6.3) which result from re-emission pathways known or assumed a priori, and which therefore need to be accounted for at the time of CORC issuance. Previously unknown or unanticipated re-emissions after issuance of CORCs are termed reversals, and are accounted for via a procedure described in the Puro Standard General Rules.[36] Such events include, for example, physical events and changes, caused by natural phenomena, which affect temporarily or permanently the behavior of carbon stored in the deep ocean.

The primary objective of identifying reversal risks is to proactively detect potential events or conditions that could compromise the permanence of the carbon storage, enabling the CO_2 Removal

[36] Available in the Puro Standard document library.

Supplier to define measures to address those risks and compensate for any reversals. A key factor in avoiding or mitigating reversal risks is the concept of a well selected and monitored deployment and sinking site, of which proper risk management is an integral part. When all of the eligibility (section 3) and risk assessment criteria (section 4.2) set in this methodology are met, the risk of reversal is considered low.

Note that this section is limited to specific assessment criteria for reversal risks. For reversal risk monitoring requirements, see section 9.7.

4.3.1. Prior to the start of the operations, the CO_2 Removal Supplier shall assess any potential sources of a reversal risk, based on the eligibility requirements (see section 3.7) and general risk assessment criteria detailed in section 4.2. The assessment shall include reversal risks arising from:

a. Natural processes, including but not limited to:
   - Progressive changes, including ocean circulation shifts due to climate change.
   - Discrete events.

b. Anthropogenic interference, including but not limited to:
   - Deep-sea mining and exploration.
   - Political or regulatory instability.
   - Fishery operations.

c. Combination of both.

4.4. Requirements for environmental and social risk assessment and management

The Puro Standard General Rules[37] contain the general requirements on environmental and social safeguards that apply to all methodologies (see also rule 4.2.1), while this section contains further requirements on assessing environmental and social risks and their impacts relevant to MCFS activities in particular.

4.4.1. The CO_2 Removal Supplier shall have in place, maintain, and abide by environmental and social safeguards to the extent required by this methodology, the Puro Standard General

[37] Available in the Puro Standard document library.

Rules[38], or any applicable local statutory requirements, in order to ensure that the MCFS activities do no "net-harm" to the surrounding natural environment or local communities.

4.4.2. The CO_2 Removal Supplier shall provide all environmental permits, assessments, and other documents related to the analysis and management of environmental and social impacts of the MCFS activities that are required by the applicable local laws and regulations.

4.4.3. The CO_2 Removal Supplier shall specifically assess the environmental and social impacts of the MCFS activity, following applicable local or national legislative requirements for an Environmental Impact Assessment (EIA).

a. The EIA shall include a comprehensive, project-specific Environmental and Social Risk Assessment, which shall be based on the normal operating conditions of the ocean storage of biomass activity. In addition to requirements set in section 4.2, the assessment shall include:

- Description of the applicable legal and regulatory framework pertaining to the assessment and management of the environmental and social impacts of the MCFS project.
- Description of the existing local environmental and socio-economic conditions (i.e. background information on the current environmental and socio-economic context in which potential impacts are assessed).
- Description of the MCFS activity in detail, including construction, operation, and decommissioning of infrastructure, and other aspects affecting the assessment of environmental and social impacts.
- Identification and description of the anticipated environmental and social impacts, including but not limited to the predetermined risks set in this methodology (see section 4.5). For example, such impacts might include any potential negative effects to:
  - Soil, air, and water quality (e.g., hydrological cycles, physical and biogeochemical properties).
  - Flora and fauna (e.g., biodiversity, habitats).
  - Human health and safety.
  - Socio-economic factors (e.g., related to land use or water resources).

[38] Ibid.

    - Local communities (e.g., due to noise, pollution, limiting access to recreationally significant areas).
    - Sites of cultural or archaeological significance (e.g. shipwrecks).
  - Include a disaster management plan, in case of any abrupt situations such as spillages or natural hazards.

b. In cases where EIA is not required by the applicable local or national legislative requirements, the CO_2 Removal Supplier shall provide documentation that robustly addresses all material environmental and social impacts, following criteria determined in the Puro Standard General Rules[39] and this methodology.

4.4.4. The CO_2 Removal Supplier shall comply with all applicable local laws and regulations relating to access and consumption of water resources. The CO_2 Removal Supplier shall furthermore recognize, respect and promote the human rights to safe drinking water and sanitation[40] as well as the right to water as laid out in the General Comment No. 15 of the United Nations Committee on Economic, Social and Cultural Rights.[41] In particular, the CO_2 Removal Supplier shall not endanger the availability, quality, or accessibility of the local water supply, as defined in article 12 of General Comment No. 15.[42]

4.4.5. The CO_2 Removal Supplier shall prepare and abide by an environment, health and safety (EHS) plan to assess and mitigate exposure to harmful chemicals. The plan shall contain at least the following elements related to environmental risks and human health risks:

a. Identification and listing of any potentially harmful chemical compounds used at any stage within the activity boundary.

b. Risk assessment and mitigation measures for chemical injuries (for example, due to inhalation, ingestion, or skin contact) considering all relevant exposure pathways.

c. Based on the local statutory requirements, a determination of threshold exposure values and/or other limit values to prevent chemically induced diseases (whether through direct exposure, or indirect exposure such as through environmental contamination where relevant), and a description of the measures to limit and monitor the exposure to harmful chemicals.

[39] Available in the Puro Standard document library.

[40] The human rights to safe drinking water and sanitation, G.A. Res 78/206, U.N. Doc. A/RES/78/206 (Dec. 22, 2023).

[41] General Comment No. 15 (2002), The right to water (arts. 11 and 12 of the International Covenant on Economic, Social and Cultural Rights), U.N. Doc. E/C.12/2002/11 (Jan. 20, 2003).

[42] Ibid., p. 5.

d. Identification of any potential pathways for chemical spills or leakages, and a description of the measures to prevent leakages and mitigate any harm to the environment or human health.

e. Emergency preparedness plan, including appropriate response procedures in case a chemical spill has occurred. The plan shall at least address:

- How to prevent any further damage.
- Equipment and methods for cleanup.
- Evacuation zones and procedures.
- First-aid procedures.

4.5. Key environmental and social risks

The environmental risks associated with MCFS approach can be broadly considered to mainly impact marine ecosystems. While the CO_2 Removal Supplier must identify, assess and evaluate all risks related to the MCFS activity within the activity boundary (see rule 4.4.3), this section outlines the key risk predetermined in the context of this methodology (table 4.2) and specific requirements for their assessment, avoidance and mitigation, when applicable.

Table 4.2. Predetermined environmental risks in the context of this methodology. Note, that the list is not exhaustive.

Risk	Description	Risk assessment	Risk minimization or mitigation
Nutrient robbing and changes in the phytoplankton growth rate	Possible negative effect on productivity both locally and in connected far-field regions of the ocean due to decreased macronutrient delivery	Pre-deployment and post-operation nutrient, carbon-fixation rate, and phytoplankton measurements; ocean current modeling.	• Pre-operation assessments inform reasonable substrate application rates • Operational measurements and modeling serve research purposes, which allows adjustment of substrate application rate in future deployments

			if necessary.
Oxygen depletion and GHG biogeochemistry	Decreased oxygen concentration in ocean deep water and surface sediments with various possible negative effects, including on GHG (N_2O, CH_4) biogeochemistry.	• Monitoring of O_2, N_2O, CH_4, and NH_4^+ concentrations. • Box model simulations of O_2 consumption in deep water.	• Appropriate operational planning of substrate application rates that avoid excessive blooms causing hypoxia. • Assessments during deployment serve research purposes, which allows adjustment of substrate application rate in future deployments if necessary.
Changes in carbonate system chemistry	Increased inorganic carbon uptake by photosynthesis could cause small changes in surface-water carbonate system	Monitoring of surface-water carbonate system pre-deployment and post-operation.	• Pre-operation assessments inform reasonable substrate application rates • Monitoring serves research purposes, which allows adjustment of substrate application rate in future deployments if necessary.
Changes in ocean chemistry	Potential adsorption of seawater anions, especially phosphate, to metal oxides in the substrate, possibly contributing to phosphate removal from ocean surface water.	Monitoring of surface water phosphate concentrations.	Assessments during deployment serve research purposes, which allows strategic adjustments in substrate composition in future deployments.

Biodiversity changes and food web disruption	Substrate-facilitated blooms could cause longer-term shifts in local plankton communities with possible impacts across the food web that might include economical impacts (e.g., on fisheries)	Monitoring of: • changes in carbon availability (e.g., via phytoplankton growth rate, TOC concentrations) • microbial community composition	• Introduction of foreign phytoplankton species prohibited • Monitoring serves research purposes, which allows strategic adjustments in future deployments.
Harmful algal blooms (HABs) and toxins production	Micronutrient additions and ecological disruptions by rapid microalgae growth might result in HABs and toxin production.	• Assessments of regional history of HABs • Monitoring of phytoplankton and microbial community composition for HAB species and, if necessary, measurement of toxins.	• Pre-operation assessments of regional history of HABs allows pre-operational adjustments • Monitoring serves research purposes, which allows strategic adjustments in future deployments.
Dimethylsulfide (DMS)	Production of additional dimethylsulfide, a climate cooling agent, may be a potential co-benefit.	Monitoring of DMS precursor concentration during operation.	Assessment serves research into potential co-benefits of MCFS.
Physical harm to larger organisms (fish, mammals and birds)	Possible ingestion of Substrate might harm larger marine organisms.	• Assess risk of ingestion • Analysis of fisheries data to understand representative species' habitat and feeding	• Use only non-toxic material in substrate • Assessments inform operational planning in ways that minimize risk
Benthic organism smothering	Potential 'clogging' of benthic organisms' feeding or breathing	Monitoring of Substrate particle density per area of seafloor using	Pre-operational planning to ensure deployment with sufficient particle distribution.

	apparatuses caused by the settling Substrate.	Lagrangian modeling.	Monitoring serves research purposes informing future deployment planning.

Nutrient robbing and changes in phytoplankton growth rate

By alleviating micronutrient deficiency, primary productivity is stimulated in HNLC regions (see rule 3.7.6). The enhanced uptake of inorganic carbon and macronutrients (primarily nitrate and phosphate) to produce biomass could potentially perturb the regional budgets of these elements.

Macronutrients might become locally depleted by MCFS activities with potential negative implications for local phytoplankton growth. Additionally, it has been argued that stimulation of primary productivity in HNLC regions might affect the nutrient availability in distant parts of the ocean ("far-field"), which are connected by ocean currents to an MCFS deployment site from which those far-field regions might have, on annual to decadal timescales, received additional nutrients that could have stimulated productivity and removed carbon (e.g., far-field; (Lauderdale et al., 2020; Tagliabue et al., 2023). Thus, at both the local and far-field levels, the reduction of macronutrients might reduce/limit the phytoplankton community production/growth rates. In the Southern Ocean, Subantarctic mode water originates in surface water that is cooled and subducted to the mid-water column, ultimately to upwell at lower latitudes, bringing nutrients to the ocean surface in the upwelling region (Carter et al., 2008; Chiswell et al., 2015). A decrease in shallow and mid-water remineralization due to rapid sinking of organic matter in MCFS projects would result in lower nutrient delivery to far-field nutrient-lean regions by upwelling mode water. Hence, stimulated productivity in HNLC regions could be considered to come at the expense of productivity in the far-field nutrient-poor regions, such as the oligotrophic gyres. It becomes necessary to weigh any CDR benefits against potential environmental and ecological impacts in far-field regions.

Hypothetically, if nutrient utilization and export efficiency of MCFS activity in HNLC regions and natural activity in far-field nutrient-poor regions were exactly identical, then MCFS activity would result in no additional CO_2 drawdown. However, MCFS activities are required to increase the export of photosynthetic biomass over the natural export efficiency (see section 3.1). Hence, MCFS activities shall stimulate biomass production that is efficiently exported to the ocean interior in HNLC regions (i.e., highly efficient CDR), which replaces natural production of biomass that is predominantly remineralized in the surface ocean in more nutrient-poor regions (i.e., highly inefficient CDR). The effects of this productivity switch on CDR are expected to be substantial, but impacts on seawater chemistry and regional marine food webs are also expected.

4.5.1. Risk of local macronutrient depletion: The CO_2 Removal Supplier shall avoid reduction of macronutrient concentrations to levels lower than than the intra-seasonal minimum as a consequence of the MCFS operation in the following ways:

a. The CO_2 removal supplier shall estimate the expected biomass removal and dispersion caused by the MCFS activity and calculate the expected associated reduction in nitrate, phosphate, and silicate concentrations and their impact in natural phytoplankton growth rate within the AOI following the requirements determined in rule 4.5.2.

b. Based on these estimates, the CO_2 removal supplier shall design the deployment approach (Substrate application rate, Substrate distribution area) in a way that avoids local reduction of macronutrients below levels exceeding AOI intra-seasonal variability.

c. The CO_2 Removal Supplier shall monitor nitrate, phosphate, and silicate concentrations during pre-deployment, fixation, and post-operation phases (table 9.3).

4.5.2. The CO_2 Removal Supplier shall assess the reduction in the natural phytoplankton growth rate due to the MCFS activity, at a minimum on the community level. The calculated reduction in the phytoplankton community growth rates following the macronutrients reduction at the deployment and sinking site shall be within the natural variation (see rule 3.7.5). To determine the reduction in phytoplankton growth rate, the CO_2 Removal Supplier shall:

a. Determine the baseline nutrient concentration at the deployment and sinking site, as determined in rule 3.7.5.

b. Determine the phytoplankton growth rate for the undisturbed ambient (baseline) conditions at the deployment and sinking site using the following equation:

$$\mu_{baseline} = \mu_{max}[N_{baseline}] \div ([N_{baseline}] + K_n) \tag{4.1}$$

Where:

Variable	Description	Unit
$\mu_{baseline}$	Specific growth rate prior to the MCFS activity.	day^{-1}
μ_{max}	Maximum growth rate.	day^{-1}
K_n	Monod constant (nutrient concentration at which the specific growth rate (μ) of microorganisms is half of the maximum growth rate (μ_{max})).	$\mu mol\ L^{-1}$
$[N_{baseline}]$	Nutrient concentration for the baseline conditions at the deployment and sinking site (see rule rule 3.7.5).	$\mu mol\ L^{-1}$

The maximum growth rate (μ_{max}) and Monod constant (K_n) shall be determined via laboratory experiments as further determined in rule 9.4.7.

c. Determine density of the substrates with accumulated microalgae and adjacent bacteria (see rule 3.6.2 and rule 9.6.13) at the end of the fixation phase, immediately prior to the export phase.

d. Utilize a Lagrangian model to estimate the substrate deployment density (kg of substrate particles per m^2). The particle density shall be directly derived from the model output.

e. Calculate the DIC uptake due to the MCFS activity, taking into consideration the specific substrate deployment density (subrule d). The DIC uptake (mol C/m^2) shall be determined with the following equation:

$$N_{C_{org}}^{Surface} = N_{C_{org}}^{1Kg} \times J^{GB} \quad (4.2)$$

Where:

Variable	Description	Unit
$N_{C_{org}}^{Surface}$	DIC taken up per deployment.	mol C / m^2
$N_{C_{org}}^{1Kg}$	The amount of C per kg of substrate.	mol C / kg of substrate
J^{GB}	The deployment density as determined in subrule d.	kg of substrate / m^2

f. Utilize the depth of the euphotic zone (rule 6.1.6) and DIC uptake (rule 3.7.16.f) to determine the deployment-specific DIC uptake as a fraction, using the following equation:

$$f_{DIC} = \frac{N_{C_{org}}^{Surface}}{d_{phot} \times DIC_0} \quad (4.3)$$

Where:

Variable	Description	Unit
f_{DIC}	Fraction of DIC taken up per deployment.	Unitless
$N_{C_{org}}^{Surface}$	DIC taken up per deployment.	mol C / m^2
d_{phot}	The depth of the euphotic zone, as determined in rule 6.1.6.	m
DIC_0	The surface DIC concentration measured in baseline (section 9.6.1, Table 9.3)	mol C/ m^3

g. Calculate the nutrient uptake for nitrate (NO_3), phosphate (PO_4) and silica (Si) (see rule 3.7.9) due to the DIC uptake using the Redfield ratio (C:N:P = 106:16:1) and typical HNLC surface nutrient concentration for each nutrient. The uptake of each nutrient shall be calculated follows:

$$N_{N_{org}}^{Surface} = N_{C_{org}}^{Surface} \times 16 \div 106 \tag{3.4}$$

$$N_{P_{org}}^{Surface} = N_{C_{org}}^{Surface} \div 106 \tag{3.5}$$

$$N_{Si_{org}}^{Surface} = N_{C_{org}}^{Surface} \times 5 \div 106 \tag{3.6}$$

Where:

Variable	Description	Unit
$N_{N_{org}}^{Surface}$	N taken up per deployment	mol / m^2
$N_{P_{org}}^{Surface}$	P taken up per deployment	mol / m^2
$N_{Si_{org}}^{Surface}$	Si taken up per deployment	mol / m^2
$N_{C_{org}}^{Surface}$	DIC taken up per deployment	mol C / m^2

The fraction of each nutrient taken up shall then be calculated as:

$$f_N = \frac{N_{N_{org}}^{Surface}}{d_{phot} \times NO3_0}, f_P = \frac{N_{P_{org}}^{Surface}}{d_{phot} \times PO4_0}, \text{ and } f_{Si} = \frac{N_{Si_{org}}^{Surface}}{d_{phot} \times Si_0}$$

h. Calculate the phytoplankton growth rate at the deployment and sinking site for the post-operations phase, using the following equation:

$$\mu_{activity} = \mu_{max}[N_{reduced}] \div ([N_{reduced}] + K_n) \quad (4.7)$$

Where:

Variable	Description	Unit
$\mu_{activity}$	Specific growth rate after the MCFS activity.	day^{-1}
μ_{max}	Maximum growth rate, determined as described in subrule b.	day^{-1}
K_n	Monod constant (nutrient concentration at which the specific growth rate (μ) of microorganisms is half of the maximum growth rate (μ_{max})), determined as described in subrule b.	$\mu mol\ L^{-1}$
$[N_{reduced}]$	Nutrient concentration after the reduction due to the MCFS activity as determined in subrule i.	$\mu mol\ L^{-1}$

The maximum growth rate (μ_{max}) and Monod constant (K_n) shall be determined via laboratory experiments as further determined in rule 9.4.5.

i. The reduction of nutrient concentration ($[N_{reduced}]$) due to the MCFS activity shall be determined with the following equation:

$$[N_{reduced}] = [N_{reduced}] \times (1 - f_{N`}) \quad (4.8)$$

j. Calculate the reduction in natural phytoplankton growth rate:

$$F_{reduced} = \frac{\mu_{baseline} - \mu_{reduced}}{\mu_{baseline}} \quad (4.9)$$

Where:

Variable	Description	Unit
$F_{reduced}$	The change in phytoplankton growth rate.	%
$\mu_{baseline}$	The baseline growth rate, determined as required in subrule b.	day^{-1}
$\mu_{reduced}$	The reduced growth rate due to the MCFS activity, as determined in subrule h.	day^{-1}

4.5.3. In cases where the risk of local macronutrients depletion and their effect on local phytoplankton growth rate exceed AOI intra-seasonal variability, the CO_2 Removal Supplier shall either reduce or mitigate the risk accordingly (see rule 4.4.3).

a. At minimum, the consequence of this shall result in a decreased Substrate application rate within the same Area of Interest, pending approval by the Issuing Body.

b. If local carbon fixation rates post-operation fall below AOI intra-seasonal variations, the difference shall be accounted for in the CORC evaluation as described in section 6.2.

4.5.4. Risk of far-field nutrient depletion: The CO_2 Removal Supplier shall assess the risk of macronutrient depletion in far-field regions due to the MCFS activity. The assessment shall include at least:

a. Assessment of any risks for the far-field depletion of macronutrient (nitrogen and phosphorus) stocks associated with large-scale application of the MCFS activity, e.g., using post-operation macronutrient measurements (rule 4.5.1, section 9.6) in combination with an ocean circulation model that tracks the water mass that is nutrient depleted due to the MCFS activity (section 9.5).

b. If evidence for far-field macronutrient depletion is found, the associated loss in carbon-fixation potential shall be accounted for in the CORC evaluation as described in section 6.2.

Oxygen depletion and GHG biogeochemistry

The enhancement of photosynthetic carbon fixation in the photic zone can increase local oxygen (O_2) production. However, as it sinks through the water column, the remineralization of natural organic matter produced at the surface might increase O_2 consumption in the ocean interior and ocean sediments. Low concentrations of dissolved oxygen, especially below the "hypoxia" threshold of 60 µmol/kg DO, can affect organisms, ecology, and biogeochemical cycles, including the potential increase of production of the greenhouse gasses nitrous oxide (N_2O) and methane (CH_4). N_2O and CH_4 are formed by the strictly anaerobic (i.e., not proceeding in the presence of O_2) processes of denitrification and methanogenesis, respectively. However, N_2O can also be formed as a side product of nitrification in the presence of ammonium (NH_4^+) and O_2, with a trend toward more N_2O formation at lower O_2 in the oxic to hypoxic range (Punshon & Moore, 2004).

4.5.5. The CO_2 Removal Supplier shall avoid decrease in the deep water dissolved oxygen (DO) concentration in excess of a 30% threshold as a consequence of the MCFS activity in the following ways:

a. Assess the risk of dissolved oxygen (DO) depletion caused by the oxidation of the Substrate in the water layer (tens of meters; based on eddy diffusion at site) overlying the sediments (see rule 4.5.7).

b. Design the deployment approach (Substrate application rate, Substrate distribution area) in a way that avoids reduction of DO in deep ocean water below the threshold specified above.

4.5.6. DO depletion in the deep ocean water overlying the sediments shall be assessed with a multi-box model, which simulates the impact of Substrate addition on DO consumption at the sediment-water interface, in compliance with the criteria determined in subrules a-e.

a. The model shall be based on the bottom current's velocity and DO concentration (from the assessment described in rule 3.7.7) and model DO consumption by reaction with organic matter in the flowing water.

b. The model shall simulate the trajectory of the bottom water current through several horizontally aligned boxes. The current brings bottom water with an initial (baseline) DO concentration into the first box and removes an equal amount of bottom water into the next box.

c. The initial DO concentration in the most "upstream" box is invariant at pre-defined value, whereas the concentration in the flow entering more "downstream" boxes depends on DO consumption in the preceding boxes.

d. Within each box, the organic matter decays with an e-folding time of one year, consuming DO in the process. A differential equation for the DO concentration can be applied, it should also take into account the mean loading of organic matter per square meter (from the Lagrangian model output) and eddy diffusion for the bottom water from literature to account for the affected water layer thickness.

e. Diapycnal eddy diffusivity may be assumed to be between 10^{-5} and 10^{-4} m^2 s^{-1} in deep water layers (Katsumata & Yamazaki, 2023). This diffusivity impacts the width of the bottom water boundary layer, affecting the DO concentration in that layer.

4.5.7. The CO_2 Removal Supplier shall demonstrate that any decrease in DO concentrations is not expected to result in increased production of GHGs such as methane and N_2O. This shall be done on the basis of bottom-water DO modeling (see rule 4.5.6) and by monitoring concentrations of these GHGs, as well as concentrations of ammonium and DO, and interpreting this information in the context of the scientific literature (Punshon & Moore, 2004).

4.5.8. Creation of hypoxic conditions (<60 µmol/kg DO) in the water column due to the operation shall be avoided by applying sufficiently moderate amounts of Substrate to avoid an excessive phytoplankton bloom (i.e., one that would be expected to decrease DO concentrations by more than 30%). The CO_2 Removal Supplier shall also monitor the DO concentration in the surface water during the fixation phase (section 9.6).

Changes in carbonate system chemistry

During MCFS project activities, enhanced photosynthetic carbon fixation is expected to consume dissolved inorganic carbon (DIC) in the surface ocean. Over a timescale of months to years, if the DIC-deficient (and CO_2-undersaturated with respect to the atmosphere) seawater remains in the surface ocean, the natural process of air-sea gas exchange will result in uptake of atmospheric CO_2 (Jones et al., 2014). It is expected that the temporary decrease in surface ocean DIC concentrations (i.e., until air-sea gas exchange drives atmosphere-surface ocean re-equilibration) will cause a temporary increase in surface water pH. Highly increased seawater pH values can cause physiological stress in some marine organisms (Dai et al., 2023; Hansen, 2002; Pedersen & Hansen, 2003), whereas moderate increase in pH may alleviate the impacts of ocean acidification, at least locally and transiently.

4.5.9. The CO_2 Removal Supplier shall avoid changes in the carbonate system that are potentially harmful to marine organisms as a consequence of the MCFS activity. Specifically, pH changes shall remain within the tolerated range of most marine organisms (pH range 7.5-8.5; (Melzner et al., 2009; Ross et al., 2011). This shall be achieved in the following ways:

a. The CO_2 Removal Supplier shall assess the risk of carbonate system changes caused by the MCFS activity in the surface water at the operation site by characterizing the carbonate system in the surface water pre-deployment and post-operation. This can be achieved by measuring two carbonate system parameters (DIC, pH, total alkalinity, pCO_2) along with temperature, salinity, and pressure, and calculate the remaining parameters, e.g., using appropriate tools such as CO2sys (Lewis & Wallace, 1998).

b. Design the deployment approach (Substrate application rate, Substrate distribution area) in a way that avoids pH changes beyond the threshold specified above.

Changes in ocean chemistry

Ocean chemistry could be altered not only by the biological changes caused by the MCFS activity, but potentially also by chemical reactions between the Substrate and dissolved compounds in seawater. Specifically, many anions are known to adsorb to surface sites on metal oxides. Therefore, the possibility of seawater anions such as phosphate, silicate, or sulfate adsorbing to metal oxides in the Substrate should be considered. This may lead to competition between phytoplankton uptake and metal oxide sorption of phosphate (potentially reducing the CDR efficiency by reducing the growth rate of phytoplankton per Substrate amount) on the one hand, and contribute to phosphate decrease during the activity, potentially leaving the seawater more phosphate-depleted than it would have been due to biological phosphate uptake alone.

4.5.10. The CO_2 Removal Supplier shall monitor phosphate concentrations during pre-deployment, fixation, and post-operation phases (table 9.3).

Biodiversity changes and food web disruption

Phytoplankton form the base of the marine food web, and stimulation of their growth by MCFS activities may be expected to affect food web structure, function, and dynamics. Changes in the community structure may lead to changes in nutrient cycling, ecosystem stability and economic disruptions (i.e. fisheries). The MCFS approach strictly excludes introduction of foreign organisms, and operations are restricted to enhancing local phytoplankton growth only (see rule 3.7.14). This significantly decreases the risk of introducing foreign organisms which may outcompete the local species present. While the risk is likely negligible, risks to the surface ocean ecosystem must be assessed and mitigated, when necessary.

4.5.11. The CO_2 Removal Supplier shall assess all potential negative impacts on food web and biodiversity at the deployment and sinking site, and demonstrate that the impacts may be either avoided or minimized. When any changes are considered as a significant risk to the food webs and biodiversity, mitigation protocols shall be utilised (see rule 4.4.2) following requirements set by the local, regional or national permitting authority (see rule 4.4.3).

4.5.12. The CO_2 Removal Supplier shall ensure that the increased productivity and carbon export caused by the MCFS activity does not significantly reduce the availability of carbon at the bottom of the food chain. This can be assessed, e.g., by pre-deployment and post-operation monitoring of phytoplankton abundance (see rule 4.5.4) and/or TOC concentrations (table 9.3). The values of these monitored parameters should not exceed AOI intra-seasonal variation.

4.5.13. The CO_2 Removal Supplier shall assess and monitor the surface ocean microbial community composition and dynamics at the deployment and sinking site as well as the control site (see rule 3.7.13) for parameters listed in table 9.2. and table 9.3. via DNA sequencing and microbial community analyses, such as metabarcoding targeting marked genes for bacterial (16S rRNA), Dynophycea (28S rRNA), and eukaryotic and Haptophyta (18S rRNA groups)

a. Prior to deployment the CO_2 Removal Supplier shall determine the environmental baseline for microbial activity as stated as determined in rule 9.3.7.

b. To track the changes in the microbial communities post-deployment, the CO_2 Removal Supplier shall conduct the measurements on surface water samples collected during each activity phase as determined in table 9.3.

c. When the changes in the microbial community pose a significant risk to the local ecosystem, mitigation protocols shall be utilized (see rule 4.2.2.d) following requirements set by the local, regional or national permitting authority (see rule 4.4.3).

Harmful algal blooms

Algal blooms become harmful when algae either accumulate to abundances that disrupt natural ecosystems or produce compounds (toxins) that harm natural marine populations or humans (e.g., (Glibert, 2006; Sellner et al., 2003). Such harmful algal blooms (HABs) can be caused by a variety of factors, including eutrophication (overabundance of nutrients), high temperatures, or the stimulation of key, toxin-producing species such as certain cyanobacteria.

4.5.14. The CO_2 Removal Supplier shall demonstrate that their activities are not expected to stimulate HABs and monitor and, if necessary, mitigate for their occurrence in the following ways:

a. By assessing the previously recorded history of naturally occurring HABs from historical oceanographic and satellite data for the AOI.

b. By monitoring the surface ocean microbial community composition and dynamics at the deployment and sinking site at baseline (pre-deployment), fixation, and post-operation phases (see rule 4.5.13). The analysis should also include taxonomic assignments obtained by metabarcoding and be compared against publicly available pathogen and marine harmful bloom (HABs) micro-organism databases. A list of species identified that are known to produce toxins (limited to those species with available reference DNA sequences in public databases) and their relative abundances should be compared between the different stages of the operation. In case of significant increase in the relative abundance of a potentially harmful species during the fixation phase, specific toxins in the surface water shall be analyzed and assessed (algal toxins; table 9.3). In case toxins are detected, strategies to avoid this effect in future operations shall be researched and developed.

Phytoplankton dimethylsulfide production

Phytoplankton, mostly nanophytoplankton, naturally emit dimethylsulfide (DMS) from the ocean surface to the lower troposphere (Keller et al., 1989; Lana et al., 2011; Matrai & Vernet, 1997; Simó & Dachs, 2002; Stefels, 2000; Yoch, 2002). Oxidation of DMS leads to the formation of sulfate aerosols, which themselves have a negative radiative (i.e., cooling) effect and also serve as cloud condensation nuclei, leading to further cooling (Charlson et al., 1987; Quinn & Bates, 2011; Sanchez et al., 2018). Thus, in addition to the CDR potential, minor direct local or regional cooling is a further possible consequence of MCFS activities (Kim et al., 2018). A possible adverse effect of enhanced DMS emission is the attraction of grazers (Savoca & Nevitt, 2014; Shemi et al., 2021), which would reduce the CDR efficiency of primary productivity stimulated by MCFS activities. Field experiments should test the effect of MCFS activity on DMS emissions and the response of grazers.

4.5.15. The CO_2 Removal Supplier shall evaluate potential impacts on DMS production in field experiments in order to create a complete picture of potential impacts of MCFS on radiative forcing by measuring DMSP concentrations in the surface-near water in the pre-deployment, fixation, and post-deployment phases.

Physical harm to larger organisms

4.5.16. The CO_2 Removal Supplier shall assess the risk of the MCFS Substrates to be ingested by large organisms such as fish, seabirds and marine mammals or any other relevant organisms inhabiting the site of operation. In cases where Substrates are ingested by larger marine organisms, the CO_2 Removal Supplier shall provide thorough assessment and research of whether this ingestion does significant harm to fish or other larger organisms before next deployment.

4.5.17. The CO_2 Removal Supplier shall collect and analyze fisheries data. This information shall be sourced from existing literature and pertinent authorities. The data extracts should map the geographic range of commercial, traditional, and recreational fishing within the AOI.

a. A review of existing literature and species records shall be conducted to identify the fish species present, with a priority on those that are protected, threatened, commercially important, or ecologically significant.

b. From this list, representative species shall be selected for a more detailed ecological characterization of their habitat and feeding strategies.

c. Finally, the potential physical and chemical effects of substrate ingestion shall be evaluated by reviewing literature on analogous materials.

4.5.18. The CO_2 Removal Supplier shall provide evidence that the substrate does not contain toxic materials that might harm living organisms (rule 3.6.9).

Benthic organism smothering

Smothering relates to potential ‘clogging’ of the feeding or breathing apparatuses of benthic organisms by settling Substrate. Smothering of benthic fauna is only likely to occur from a consistent layer of fine sediment of 3 mm thickness or above (Fjukmoen et al., 2024).

4.5.19. The CO_2 Removal Supplier shall analyze available scientific literature to assess any possible occurrence of known organisms vulnerable to particulate smothering. This shall be included in the characterization of the seafloor conditions at the deployment and sinking site (rule 3.7.8).

4.5.20. The CO_2 Removal Supplier shall ensure that the density of Substrates on the seabed does not create a consistent layer on the sediment and remains at the lower end of the epifauna sediment deposition tolerances for deep-sea environments (Fjukmoen 2019) by applying a deployment approach that ensures sufficient dispersion of the Substrate.

4.5.21. The CO_2 Removal Supplier shall estimate the density of Substrates on the seabed using a Lagrangian model simulating the trajectory of the sinking Substrate (rule 3.8.2) with the model taking into account inter-annual variability of currents and wind based on multi-year regional datasets.

5. Quantification

5.1. General principles

In general, a CORC represents the net removal of 1 tonne CO_2e removed from the atmosphere. In the specific context of MCFS, the CO_2 removal results from carbon fixation and sinking, which remove the CO_2 from the atmosphere and sequester it as organic and inorganic carbon in the deep ocean and the sediments.

The overall principle of the CORC calculation is that the CO_2 Removal Supplier first determines the gross amount (in metric tonnes) of CO_2e sequestered as a result of the project activity (C_{stored}) over a given monitoring period. Various deductions are then made, such as any potential CO_2e losses (C_{loss}), supply chain emissions $(E_{project})$, the effect of the unmitigated negative ecological, market and activity-shifting emissions $(E_{indirect})$ and baseline carbon removal $(C_{baseline})$, if applicable. The resulting net amount of CO_2e sequestered is credited as CORCs (figure 5.1). Any form of avoided emissions relative to the baseline scenario are never included in the calculations.

$$\text{CORCs} = C_{\text{stored}} - C_{\text{baseline}} - C_{\text{loss}} - E_{\text{project}} - E_{\text{leakage}}$$

	CORCs	C_{stored}	$C_{baseline}$	C_{loss}	$E_{project}$	$E_{leakage}$
Description	Net amount of CO_2-eq removed by the MCFS activity during the reporting period.	Gross amount of CO_2-eq stored via increased carbon fixation and increased sinking efficiency	Total amount of CO_2-eq which would have been stored in the absence of the removal activity, if any.	Total GHG re-emissions during the storage period.	Total life cycle emissions arising from the whole supply chain of the MCFS activity.	Total indirect GHG emissions resulting from unmitigated negative impacts associated with the MCFS activity.
Units	Tonnes of CO_2e	Tonnes of CO_2e	Tonnes of CO_2e	Tonnes of CO_2e	Tonnes of CO_2e	Tonnes of CO_2e

Figure 5.1. Equation for the calculation of the amount of CORCs supplied by the MCFS activity over a given Monitoring Period.

Each component of the CORC equation is defined in the following subsection (section 5.2). Detailed rules on the quantification of each component are presented in sections 6, 7 and 8. For each component, the rules define whenever applicable other equations with measurement variables and constants to use. Moreover, the measurement model and its components are the basis of a monitoring system described in section 9. Finally, this measurement model also provides the framework for the estimation of uncertainty of the net carbon dioxide removal.

It should be noted that although the CORC equation is presented as a total over the monitoring period, many of the intermediary calculations are in fact performed and reported at the level of individual Substrate batches produced and deployed, thereby capturing differences between sources of variability. For ease of reading, equations in this methodology use an implicit notation where sums over batches are shown.

5.2. Overall equation

5.2.1. The overall number of CORCs (i.e. the total net amount of CO_2 removed) during a Monitoring Period shall be calculated as follows (see also figure 5.1 for an illustration):

$$CORCs = C_{stored} - C_{baseline} - C_{loss} - E_{project} - E_{leakage} \tag{5.1}$$

Variable	Description	Unit
$CORCs$	Net amount of CO_2 equivalents removed by the MCFS activity.	tCO_2e
C_{stored}	Gross amount of CO_2 stored via increased biomass carbon fixation and higher export efficiency. Further requirements on the calculation of this term are given in section 6.1.	tCO_2e
$C_{baseline}$	Total amount of CO_2-eq which would have been stored in the business-as-usual case in the absence of the removal activity. Further requirements on the calculation of this term are given in section 6.2.	tCO_2e
C_{loss}	Total amount of CO_2-eq which is expected to be re-emitted back to the atmosphere and can no longer be considered durably stored. Further requirements on the calculation of this term are given in section 6.3.	tCO_2e
$E_{project}$	Total amount of CO_2-eq that is emitted along the supply chain of the removal activity. Further requirements on the calculation of this term are given in section 7.	tCO_2e
$E_{leakage}$	Total amount of CO_2-eq that is emitted indirectly due to unmitigated negative ecological, market, and activity-shifting leakage resulting from the MCFS activity. Further requirements on the calculation of this term are given in section 8.	tCO_2e

5.2.2. The length of a Monitoring Period must comply with the Puro General Rules and the cadence of the Output Audits.

5.3. Requirements for robust quantification of net carbon removal

5.3.1. The CO_2 Removal Supplier shall follow robust and auditable monitoring, measurement and reporting practices for the data needed for the calculation of CORCs resulting from the removal activity, in accordance with section 9 (monitoring), section 10 (measurement), and section 11 (reporting).

5.3.2. The CO_2 Removal Supplier shall quantify the combined uncertainty from the components included in the equation 5.1, in accordance with the relevant parts of the ISO/IEC Guide 98-321[43] as further described in section 10.

5.3.3. The CO_2 Removal Supplier shall have in place, maintain, and utilize an information system to keep records of any events affecting the amount of CORCs resulting from the MCFS of activity.[44] These records must include time stamped, quantitative information such that their effect on the Output volume of the monitoring period can be quantified. These records must be available to the Auditor, for the Production Facility Audit and Output Audits.

5.3.4. The CO_2 Removal Supplier shall follow robust and auditable measurement practices and protocols for the data needed for the calculation of the quantity of CORCs resulting from the MCFS activity.

[43] ISO/IEC Guide 98-3:2008 Uncertainty of measurement - Part 3: Guide to the expression of uncertainty in measurement.

[44] Examples of such events include any deployment or loss events, as well as the construction or replacement of any facilities, machinery or equipment (which would affect overall supply chain emissions).

6. Determination of stored carbon

6.1. Carbon stored (C_{stored})

6.1.1. The gross amount of eligible carbon stored into the deep ocean and the sediment (C_{stored}) shall be calculated as follows:

$$C_{stored} = (C_{fixed}) \times (SE_{project}) \times AS \quad (6.1)$$

Where:

Variable	Description	Unit
C_{stored}	The gross amount of eligible carbon stored into the deep ocean and the sediment at the time of the project.	tCO_2e
C_{fixed}	The net amount of fixed carbon that accumulates on the substrate due to photosynthesis and its derivatives, exported below the euphotic zone. Further requirements for the determination of this term are given in rule 6.1.2.	tCO_2e
$SE_{project}$	The sinking efficiency ($SE_{project}$) is the ratio of C_{fixed} that reaches the seafloor of the deployment and sinking site. A $SE_{project}$=1 indicates that 100% of C_{fixed} is deposited via sinking to the seafloor of the project area. Further details for the determination of this term are given in rule 6.1.7.	Unitless
AS	The air-sea gas exchange term (AS) shall consider the fraction of the surface ocean CO_2 deficit caused by MCFS that has equilibrated with the atmosphere after 10 years. An AS=1 indicates that 100% of the CO_2 deficit has equilibrated with the atmosphere leading to a 1:1 uptake of atmospheric CO_2 to ocean CO_2 removal. Incomplete CO_2 equilibration will lead to AS<1. Further details for the determination of this term are given in rule 6.1.9.	Unitless

6.1.2. The CO_2 Removal Supplier shall calculate the total amount of fixed carbon that accumulates on the substrate (C_{fixed}) as measured at the bottom of the euphotic zone as follows:

$$C_{fixed} = M_{substrate} \times f_{sunk} \times C_{org} \times \frac{44}{12} \quad (6.2)$$

Where:

Variable	Description	Unit
C_{fixed}	The net amount of fixed carbon that accumulates on the substrate due to photosynthesis within the euphotic zone.	tCO_2e
$M_{substrate}$	Total mass of substrates deployed based on the dry weight measured prior to deposition. Further requirements for the determination of this term are given in rule 6.1.3.	Tonnes
f_{sunk}	The fraction of deployed substrates that has sunk out of the euphotic zone after the full floating phase. Further details for the quantification of this term are given in rule 6.1.5.	Unitless
C_{org}	The net amount of organic carbon accumulated on one tonne of substrates, after the full fixation phase period or measured at the bottom of the euphotic zone. Further details for the quantification of this term are given in rule 6.1.6	Tonne/Tonne
$\frac{44}{12}$	Mass conversion factor from elemental carbon to a corresponding amount of carbon dioxide, calculated as the ratio between the molar masses of carbon dioxide and carbon.	tCO_2e/tonne

6.1.3. The CO_2 Removal Supplier shall measure the total dry mass of the Substrates ($M_{substrate}$) prior to the deployment of the Substrates. The total mass shall be measured as close in time to deployment as possible. The total mass shall be measured by direct on-site measurement with reliable, calibrated weighing equipment following industry standards, such as load cells or weighbridges.

6.1.4. The CO_2 Removal Supplier shall quantify the fraction of deployed substrates that successfully sink out of the euphotic zone (f_{sunk}) by assessing f_{sunk} for a controlled deployment within a semi-enclosed in-situ platform that is deployed in parallel with the main MCFS deployment. The CO_2 Removal Supplier may use Echosounders or similar instruments that track particle plumes in-situ to assess f_{sunk}. See rule 9.6.16 for further details on the controlled deployment.

6.1.5. The CO_2 Removal Supplier shall collect statistically significant samples (for further requirements on sampling, see section 10.4) of each batch of deployed Substrates collected from:

a. The surface ocean at the end of the fixation phase, prior to export phase.

b. Below the euphotic zone during the export phase.

The samples shall be analysed for carbon content (C_{org}) of the phytoplankton, adjacent bacteria and their derivatives attached to a given sample of the Substrate. The organic carbon concentration of the Substrate material shall be subtracted, when applicable. Further requirements on the measurement of organic carbon are determined in rule 9.3.3.

6.1.6. The CO_2 Removal Supplier shall determine the depth of the euphotic zone as described in rule 3.7.10. b.

6.1.7. The CO_2 Removal Supplier shall calculate the sinking efficiency of the project ($SE_{project}$) as follows:

$$SE_{project} = 1 - \int_{z_{eu}}^{z_{stored}} e^{-R(T_z, O_{2z})z}\, dz \quad (6.3)$$

Where:

Variable	Description	Unit
$SE_{project}$	The sinking efficiency is the ratio of C_{fixed} at the bottom of the euphotic zone as compared to the C_{fixed} that reaches the seafloor (see rule 6.1.2).	Unitless
R	The remineralization rate of fixed carbon on the substrate as the substrate sinks to the seafloor. R will vary with depth as temperature (T_z) and oxygen (O_{2z}) change with depth. R is based on lab and field measurements. Further requirements for the determination of this term are given in rule 6.1.8.	fraction mass/m
T_z	In-situ temperature profile (see rule 9.3.7).	°C
O_{2z}	In-situ dissolved oxygen profile (see rule 9.3.7).	nmol/L
z_{eu}	Depth of the euphotic zone (rule 6.1.6).	m
z_{stored}	Depth at which a water mass will remain in the deep oceans for a period of at least 200 years (determined in the durability assessment, see rule 3.7.12).	m

z_{stored} refers to the depth below which carbon remineralized during or after sinking is considered durably sequestered, as it remains isolated from the atmosphere for at least 200 years. This threshold represents the point at which deep ocean water masses are no longer part of the short-term carbon cycle due to their long residence times and lack of contact with the surface ocean. While remineralization occurs throughout the water column, only the portion that occurs above z_{stored} is expected to be re-emitted to the atmosphere on timescales shorter than 200 years.

6.1.8. The rate of remineralization (R) shall be determined based on the following equation from (Cram et al., 2018), or similar peer-reviewed scientific publication which includes an oxygen and temperature dependence:

$$R(T_z, O_{2z}) = -\frac{d_0}{w}\left(Q_{10}^{(T_z-T_0)/10}\right)\left(\frac{O_{2z}}{k_{O2}+O_{2z}}\right) \quad (6.4)$$

Where:

Variable	Description	Unit
d_0	The non-sinking remineralization rate of substrate after microalgal growth (McDonnell et al., 2015). Further requirements for quantifying this term are given in rule 9.4.8.	fraction mass/d
w	Sinking speed of substrate below the euphotic zone. Further requirements for quantifying this term are given in rule 9.6.3.	m/d
Q_{10}	The change in remineralization for every increase of 10°C as compared to the remineralization for a set reference temperature (T_0). For the open ocean, a Q_{10} value of 2.4 for a T_0 value of 4°C shall be used (Quinlan, 1980, 1981; Lima et al., 2014)	Unitless
T_0	Reference temperature for a given Q_{10}. For the open ocean, a $T_0$of 4°C shall be used (Cram et al., 2018).	°C
T_z	In-situ temperature profile (see rule 9.3.7).	°C
k_{O2}	Half saturation constant for aerobic microbial metabolic activity based upon a Michalis Menton O_2 dependence. The CO_2.Removal Supplier may use a half saturation	µmol/L

	constant of 4 µmol/L or may measure it through lab experiments (Laufkötter et al., 2017).	
O_{2z}	In-situ dissolved oxygen profile (see rule 9.3.7).	µmol/L

The minimum requirements for using different equations to determine the rate of remineralization are as follows and pending approval by the Issuing Body:

a. The equation is from a peer-reviewed scientific publication.

b. R is a function of base remineralization rate or the remineralization length scale.

c. R is a function of sinking speed.

d. R is a function of temperature and oxygen.

6.1.9. The determination of the air-sea gas exchange (AS) shall consider the fraction of equilibrated CO_2 flux based on global ocean biogeochemical models that assess the potential of CO_2 uptake after surface ocean CO_2 removal. Global ocean models are necessary for quantifying AS because the potential of CO_2 equilibration at the sea surface depends on the balance between air-sea gas exchange rates and ocean mixing and subduction timescales within the Area of Interest. For the purpose of this methodology, AS shall be defined based on the Direct Ocean Removal (DOR) model results using the same modeling framework as Zhou et al. (2025)[45], which can be accessed using the online interactive map from CarbonPlan[46]. The requirements for determining AS for the deployment region is detailed in subrules a-c.

a. AS shall be determined based on the "Efficiency" variable of the DOR interactive tool with the "Storage Loss" set to 0%. In this methodology, the storage loss due to re-emission of fixed carbon (C_{loss}) is quantified separately in section 6.3.

b. The "Intervention Month" shall be set to the closest month of deployment to account for the seasonal dependence of AS.

c. AS shall be determined based on the net efficiency at Year 10 for the model region that contains the geographic bounds of the Area of Interest (AOI). If the bounds of the AOI cross multiple model regions, the model region that contains the largest portion of the AOI shall be used.

[45] Zhou et al. (2025) refers to the publication regarding an OAE efficiency tool that was published prior to the DOR efficiency tool. While a peer-reviewed publication for the DOR tool is not yet available, our understanding is that the modeling framework of the DOR tool mirrors that of the OAE tool.

[46] Chay et al. 2025 "Mapping the efficiency of direct ocean removal", CarbonPlan

REMARK ON THE AIR-SEA GAS EXCHANGE: The Direct Ocean Removal (DOR) efficiency tool developed by [C]Worthy and CarbonPlan provides an open-access, third-party developed modeling framework and dataset to assess the re-equilibration rate for abiotic surface ocean DIC removal over time. The intended use of this tool does not include the biological removal of DIC, such as MCFS, which has additional concerns and complexities regarding the impacts of regional biological perturbations on ocean chemistry and global nutrient cycling. For the purposes of this methodology, the DOR tool is strictly used to quantify the re-equilibration of the DIC-depleted surface water mass based on the net export of organically fixed carbon below a 200-year permanence depth. Specifications for how the DOR tool is applied is detailed in rule 6.1.9.

Puro.earth recognizes that several caveats of using the DOR tool still remain. Process-specific caveats include differences in the distribution of the DIC perturbation (surface layer vs. euphotic zone) and potential impacts to alkalinity which result from nutrient uptake. General caveats also include uncertainties associated with the DOR model's coarse resolution and lack of interannual variability. Other models to assess the air-sea gas exchange are available, some of which may be able to assess the efficiency on a higher resolution using e.g. regional datasets or in certain cases, in-situ measurements. Puro.earth supports the development and applicability of such models, and acknowledges that future advances in model development may provide additional information for developing new air-sea flux quantification frameworks which may better represent biological processes and site-specific characteristics.

6.2. Baseline removal ($C_{baseline}$)

The baseline is a conservative scenario of what durable carbon removal and sequestration likely would have happened without the MCFS project. This section defines requirements for determining a baseline scenario as well as considering the potential natural carbon removal occurring at the deployment site and in the wider oceanic system, i.e. remote regions which might be impacted by the project's use of phytoplankton and nutrients.

In the baseline scenario, without an MCFS intervention, phytoplankton naturally absorb carbon from the ocean, convert it into biomass. This carbon either remains trapped within the euphotic zone where the marine food web recycles it through consumption and respiration or it is exported to depth. In this natural scenario, the potential of carbon export is limited, as most of the carbon is rapidly recycled and returned to the atmosphere (Siegel et al., 2023). When MCFS is deployed into HNLC ocean conditions, it both stimulates increased carbon uptake into phytoplankton biomass, and enhances the export of that biomass to deeper waters.

6.2.1. As CO_2 export occurs naturally, the CO_2 Removal Supplier shall assess the baseline using the following equation:

$$C_{baseline} = NPP_{baseline} \times TE_{baseline} \tag{6.5}$$

Where:

Variable	Description	Unit
$C_{baseline}$	Total amount of CO_2 that would naturally be exported below a reference depth of 100 m below the euphotic zone without the MCFS intervention (Buesseler et al., 2020).	tCO_2
$NPP_{baseline}$	The amount of fixed carbon that accumulates as biomass due to photosynthesis minus the effects of respiration.	tCO_2
$TE_{baseline}$	The ratio of net primary productivity that reaches the reference depth of 100 m below the euphotic zone. TE=1 indicates that all of the fixed carbon has been exported (via gravitational sinking) 100 m below the euphotic zone TE=0.5 indicates that 50% of the removed carbon has been exported 100 m below the euphotic zone, and so on.	Unitless

6.2.2. The CO_2 Removal Supplier shall determine $NPP_{baseline}$ for the Area of Interest (see rule 3.7.9) from historic datasets. Datasets may be any combination of satellite, BGC Argo and other autonomous measurements, and in-situ sampling taken in the Area of Interest within the seasonal window of deployment. Deployment season shall be defined based on the mean monthly mixed layer depth. The historic dataset shall contain at least 15 years of data. $NPP_{baseline}$ shall be defined as a range using the mean ± 1 standard deviation of the historic dataset.

6.2.3. The CO_2 Removal Supplier shall take in-situ profile measurements within the deployment and sinking site (rule 9.6.6) prior to deployment to measure parameters outlined in table 9.3 including NPP.

6.2.4. After MCFS has been deployed and the floating phase has concluded, the CO_2 Removal Supplier shall conduct additional measurements (rule 9.6.6) in the deployment and sinking site to determine the NPP post-deployment within the deployment and sinking site. The mean NPP shall be compared against the control site NPP (rule 9.6.3) and the historic

$NPP_{baseline}$ range (rule 6.2.2) to check that the site NPP falls within the historic $NPP_{baseline}$ range.

6.2.5. Any reduction in NPP within the deployment and sinking site as a result of MCFS shall be determined as the difference between the post-deployment mean NPP (rule 6.2.4) and the control site with historic $NPP_{baseline}$ range (rule 6.2.2).

6.2.6. $TE_{baseline}$ shall be determined within the Area of Interest using a 10 year average export efficiency during the relevant season from historic datasets. Datasets shall include satellite measurements, such as those from MODIS, PACE, or other equivalent satellites with at least a 1 km spatial resolution and two overpasses per month temporal resolution. Estimates of export efficiency shall be determined according to the approaches described in Siegel et al. 2014, Westberry et al. 2012, or Jönsson et al. 2023 or through the framework proposed in Nowicki et al. 2022. The CO_2 Removal Supplier may further validate the estimated export efficiency using either 1) field measurements, 2) published datasets, or 3) validated models.

6.2.7. The CO_2 Removal Supplier supplier shall compare the measured $TE_{baseline}$ shall be compared to the post-deployment to transfer efficiency (100 m below the euphotic zone) to prove that the MCFS activity is not negatively affecting any potential natural carbon sinking process occurring at the storage site.

6.2.8. The CO_2 Removal Supplier shall use local dynamics models to identify watermass connectivity to assess the downstream effects of the nutrient utilization that occurs during the MCFS. The CO_2 Removal Supplier shall identify any relevant nutrient limitation thresholds such as those for Nitrate, Fe, P, and Si and prove that the deployment of MCFS does not cause any downstream region to cross said threshold.

6.3. Carbon Losses (C_{loss})

The definition for losses (C_{loss}) applies to re-emission pathways known or assumed a priori, and which therefore need to be accounted for at the time of CORC issuance. Previously unknown or unanticipated re-emissions after issuance of CORCs are termed reversals, and are accounted for via a procedure described in the Puro Standard General Rules[47] (see section 4.3 and section 9.7).

For the purposes of this methodology, a loss pathway is defined as any biogeochemical event or process following the initial CO_2 sequestration through the sinking of organic matter into the storage location, which results or can reasonably be expected to result in a portion of the sequestered carbon being released back to the atmosphere over the minimum 200-year storage period. In particular, the

[47] Available in the Puro Standard document library.

primary loss pathway associated with MCFS is the re-emission of CO_2 to the atmosphere due to remineralization and decomposition of organic matter to DIC, followed by deep water circulation and subsequent return to the atmosphere. This return timescale can range from decades to millennia, and it is highly dependent on the ocean region and depth of the carbon deposition (Siegel et al., 2021).

6.3.1. The CO_2 Removal Supplier shall quantify and account for all loss (re-emission) pathway(s). Losses that occur after the carbon reaches the storage location and prior to the minimum storage period of 200 years shall be reflected in C_{loss}. To assess the amount of carbon that will be re-emitted over the 200-year storage period, physical and biogeochemical oceanographic modeling shall be applied (rule 6.3.4), accounting for ocean dynamics including currents, temperature, and chemical conditions (see section 9.6). The estimated re-emission over the storage period of a project shall be subtracted from the quantity of sequestered carbon.

6.3.2. Losses due to 1) respiration by macro- and micro-fauna and 2) carbon shedding and remineralization at the sinking phase are expected to occur in advance of the carbon C_{stored} term and should not be included within C_{loss}, with the following justifications:

a. Losses that occur in advance of the sinking phase, including respiration by macro- and micro-fauna, shall be reflected within the C_{stored} term and are thus not included within C_{loss}. This is because the measurements of fixed organic carbon reflect the net carbon removed (photosynthesis minus respiration).

b. Losses that occur during the sinking phase, including carbon shedding and remineralization, shall be reflected within the C_{stored} term and are thus not included within C_{loss}. This is because the amount of carbon that reaches the site of carbon storage is captured within $SE_{project}$.

6.3.3. The loss due to re-emission of remineralized DIC via ocean ventilation (C_{loss}) shall be quantified as follows:

$$C_{loss} = (C_{fixed} \times SE_{project}) \times F_{vent} \tag{6.6}$$

Where:

Variable	Description	Unit
C_{loss}	The cumulative re-emission of remineralized DIC via ocean ventilation over 200 years for a specific deployment and sinking site.	tCO_2e
$C_{fixed} \times SE_{project}$	The gross amount of fixed carbon stored into the deep ocean and the sediment at the time of the	tCO_2e

	project (rule 6.1.1)	
F_{vent}	The net fraction of remineralized DIC re-emitted to the atmosphere over the minimum 200-year storage period. This value is derived from ocean circulation models (rule 6.3.4).	Unitless

For the purposes of CORC evaluation, the most conservative approach for calculating C_{loss} is used such that all of the stored organic carbon (C_{stored}) is assumed to be remineralized to DIC as it reaches the seafloor.

6.3.4. F_{vent} shall be quantified for a specific deployment and sinking site through integration of far-field biogeochemical models and global ocean biogeochemical models that account for realistic ocean carbon cycling and CO_2 air-sea gas exchange processes, as detailed in subrules a-c.

a. F_{vent} shall be determined at the 200-year horizon for a specific deployment and sinking site and pre-determined deposition depth (e.g. seafloor) based on coupled model results of far-field and global circulation models.

b. Far-field modelling shall be used to provide high resolution circulation and biogeochemical dynamics of the remineralized DIC within kilometers of the deployment and sinking site to assess the short-term (≤1 year) dispersion and sequestration of the remineralized DIC after its deposition. The CO_2 Removal Supplier shall use the following modeling packages or model outputs to conduct local dynamic modeling specific to their deployment and sinking site, such as Delft3D[48], MIKE 3[49], TELEMAC 3D[50], FVCOM[51], or similar.

c. A 3D map of DIC dispersion and sequestration from the far-field model shall be used to define the initial DIC deposition grid(s) in the global biogeochemical model to assess the long-term (200 years) ventilated fraction of the remineralized DIC (F_{vent}). The DIC map from the far-field model shall be aligned to the model resolution of the global model based on the best match of latitude, longitude, and depth. If the DIC map from the far-field model spans across multiple model grids in the global model, the volume-weighted mean F_{vent} across the impacted model grids shall be used. To standardize the quantification of F_{vent}, the global

[48] Delft3D modeling suite.

[49] MIKE 3 Wame FM.

[50] TELEMAC-3D.

[51] FVCOM.

model results from Nowicki et al. (2024) shall be used, which has been peer-reviewed and is publicly available online. Approved models may be updated with continued scientific advancements and pending the Issuing Body.

7. Determination of project emissions

7.1. General life cycle assessment requirements

7.1.1. The CO_2 Removal Supplier shall calculate the whole life cycle project emissions of the carbon removal activity for every monitoring period, via a life cycle assessment (LCA) model that follows the scope defined in this section of this methodology, and following the general principles defined in ISO-14040/44[52] and the ISO-14064 series. Note however that methodology rules take precedence over these standards.

7.1.2. The LCA Model for the "microalgae carbon fixation and sinking" (MCFS) activity shall be developed in a digital tool that enables complete and transparent verification of the calculations, from input activity data to selection of emission factors. The digital tool can either be:

a. A spreadsheet LCA model, required to be built using the template provided by Puro.earth.

b. A non-spreadsheet tool (e.g. dMRV platforms) provided that at least the same level of transparency and verifiability is achieved by the tool as enabled by the Puro.earth LCA spreadsheet model, and that data and model structure can be inspected and extracted by a third party.

7.1.3. An LCA Model Description must be provided, alongside the LCA Model, to explain how the LCA Model was developed and demonstrate its representativeness for the Production Facility. This document must outline each emission source, detailing what it represents, the relevant activity data, how it is monitored, and the emission factors chosen, along with justifications for their appropriateness. Additionally, it must specify any assumptions or omissions made in the inventory and explains the calculation of key parameters, such as allocation factors. The document must also be aligned with the Monitoring Plan. This LCA Model Description is meant to support third-party auditors in their verifications as well as be the basis for public disclosure of the LCA modelling approach as part of the Project Description.

7.1.4. The LCA Model and its Description must be validated during the Production Facility Audit by the third-party auditor.

7.1.5. The LCA Model and its Description may be updated by the CO_2 Removal Supplier during the course of the crediting period to reflect changes that have occurred within the

[52] ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework and ISO 14044:2006 Environmental Management - Life cycle assessment - Requirements and guidelines

operations of the Production Facility (e.g. calculation of emissions for several types of MCFS applications, while initially only one type of MCFS application was envisioned). Any such change must be declared and reported at the next Output Audit, during which the updated LCA Model and its Description shall be re-validated by the third-party auditor.

REMARK: An LCA Model Description is a term defined by Puro.earth and differs from a traditional LCA Report under ISO-14040/44. A standard LCA Report includes an introduction, goal and scope definition, inventory modelling, results, sensitivity analysis, and interpretation. However, this format is not suited to the Puro Standard, as its key elements are either covered in other project documents (e.g., Project Description, CORC Report Summary) or not relevant for the CORC issuance process (e.g. an LCA Report contains static results and figures while CORC issuance requires updated data for each period). Puro.earth opts for a concise LCA Model Description, ensuring efficiency for CO_2 Removal Suppliers and Auditors while avoiding redundancy.

7.1.6. The CO_2 Removal Supplier must update the LCA model with operational activity data at every monitoring period, where relevant. The resulting updated project emissions must be used for reporting and verification of CORCs during the Output Audit.

7.1.7. The CO_2 Removal Supplier must provide the supporting evidence to the operational activity data that was used in the calculation, to enable verification of the third-party auditor during the Output Audit. Supporting evidence can be in various forms e.g. records of activity, energy meter readings, utility bills, sensor data. Whenever assumptions are made, these shall be conservative and supported by some form of evidence. Part of this evidence may be required to be submitted to Puro for review, while other evidence may be sufficient to have available for the audit. The evidence required to be submitted to Puro is specified elsewhere, in Puro's operative documents, but typically includes biomass records, MCFS records, energy use, material use (as specified mostly in eligibility requirements, see section 3). In any case, all supporting data must be available to the auditor upon request.

7.1.8. The LCA model shall be based on separate life cycle inventories (LCI) of operational and foreground embodied emissions according to the rules in this methodology. In practice, all operational emissions are calculated and reported for each monitoring period (see section 7.3), while foreground embodied emissions are determined at the first Facility Audit and then amortized over time (see section 7.4).

7.1.9. The LCA shall calculate the climate change impact of the activity, characterized using 100-year global warming potentials (GWP100) for greenhouse gases from the IPCC Sixth

Assessment Report[53]. Other environmental impact categories may be included but are not required.

> **REMARK:** Many public LCA data sources for emission factors, as well as literature data, have not yet been updated to reflect the changes of GWP_{100} from the latest IPCC Assessment Report. Those changes are however deemed minor, and CO_2 Removal Suppliers should strive to use the most up-to-date emission factors available.

7.1.10. The emission factors used in the LCA shall comply with the following elements:

a. include at least the contribution of major greenhouse gases (fossil CO_2, biogenic non-renewable CO_2, CH_4, N_2O).

b. include a full-scope of emissions (i.e., including upstream and downstream emissions, or so-called supply chain emissions, as opposed to emission factors used for greenhouse gas inventory purposes). Note that it is common to use multiple emission factors to represent the full-scope of an activity, e.g. one factor for direct emissions and one or several factors for upstream and downstream emissions.

c. do not include any recycling or substitutions terms (i.e. diminishing the impact of the activity).

d. be geographically appropriate to the location of the activity.

Further, The CO_2 Removal Supplier may use emission factors from publicly available or commercial databases or developed by peer-reviewed studies complying with the above elements.

7.1.11. The CO_2 Removal Supplier may purchase and use Guarantees of Origin (GOO), Renewable Energy Certificates (REC), or other similar certificates of energy attributes to claim lower GHG emission intensity for its direct energy consumption and use them to calculate the corresponding project emissions. The certificates shall follow all of these conditions:

a. The purchased certificates originate from the same physical grid or network as where they are consumed (i.e. same spatial resolution).

b. The purchased certificates have been issued within the same calendar year as when they are consumed (i.e. same temporal resolution).

[53] Intergovernmental Panel of Climate Change (IPCC) Sixth Assessment Report 2020 (AR6), Section 7.6.1.1 Radiative Properties and Lifetimes.

c. The purchased certificates specify the energy source or mix of sources, so that a carbon footprint can be calculated and used in the LCA (i.e. non-zero value).

d. The purchased certificates specify when the production capacity of the energy source or mix of sources was commissioned, and that information is then disclosed by the CO_2 Removal Supplier as part of the Output Audit. The information on the year of commissioning of the energy asset is an indicator of the additionality of the renewable energy production, allowing to distinguish between already existing assets and more recently built assets.

e. The amount of purchased certificates matches with the amounts of low-carbon energy declared in the LCA calculations.

f. The CO_2 Removal Supplier provides evidence of purchased certificates at each Output Audit or alternatively reverts to using market average emission factors if certificates are no longer purchased.

7.1.12. For transparency, interpretability and auditing purposes (i.e., verification of claims), the climate change impact calculated in the LCA shall be presented in a disaggregated way exhibiting the contributions of the different emission sources for each unit process described in figure 7.1 and table 7.1

7.1.13. Public disclosure of LCA results in the Puro Registry (i.e. the verified LCA results after each Output Audit) may be aggregated to a level sufficient to protect sensitive information or licensed LCA data, as agreed with the Issuing Body. However, the aggregation shall at least disclose the level 1 and level 2 contributions, as well as certain level 3 contributions (e.g. direct land use change emissions) as further defined in table 7.1 in the Summary section of this chapter.

7.1.14. If co-products with a meaningful use outside the process boundaries are generated during the activity, an allocation of the relevant life cycle stages between the co-products may be applied. The allocation shall follow the rules in section 7.5 for different unit processes, and for allocation situations not covered in the methodology, resort to the general approach defined in EN 15804+A2[54] or ISO 14044:2006[55].

7.1.15. If waste, recycled or post-consumer secondary resources are used as input to the activity (e.g., recycled steel or plastic), it is permissible and recommended to apply the cut-off

[54] EN 15804:2012+A2:2020 Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products.

[55] ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework and ISO 14044:2006 Environmental Management - Life cycle assessment - Requirements and guidelines

system model approach[56] for waste, recycled and post-consumer secondary products in the LCA. Specifically, the environmental burdens from disposal of such post-consumer secondary resources shall be excluded from the system boundary, but the supply, transformation and handling of the secondary resources must be included from the start of the end-of-waste point.[57]

7.1.16. The CO_2 Removal Supplier shall coordinate data collection and LCA modeling with any external operators[58] to the level necessary to ensure compliance with this methodology and the Puro Standard requirements.

7.2. Methodology-specific life cycle assessment requirements

7.2.1. The **functional unit** of the LCA shall be "one (1) metric tonne of CO2 captured by microalgae grown on a given Substrate and deposited in the deep ocean for long term storage".

7.2.2. The system boundary is set **cradle-to-grave** and shall include operational and embodied life cycle emissions (i.e., upstream and downstream activities), and calculated using the following equation:

$$E_{project} = E_{ops} + E_{emb} \tag{7.1}$$

Where:

Variable	Description	Unit
$E_{project}$	Lifecycle emissions associated with the operation of the project during the monitoring period and the amortized portion of the lifecycle's embodied emissions.	tCO_2e
E_{ops}	Lifecycle emissions of materials and energy used associated with the operation of the project during the monitoring period.	tCO_2e

[56] Description of the cut-off system model is available on the website of the ecoinvent life cycle database. This approach can also be described as a "polluter-pay" approach, as the emissions from waste treatment are attributed to the previous life cycle.

[57] This aligns with the European Commission 2023 targeted revision of the Waste Framework Directive and the proposal to include end-of-waste criteria. Accessed on 15 May 2025.

[58] Data required for performing the LCA of an MCFS activity originates from multiple parties, and most importantly from the operator of the substrate sourcing and processing, the operator of the substrate deployment system, and the logistics operators. See also rule 3.3.5.

Variable	Description	Unit
E_{emb}	Sum of lifecycle emissions associated with production, use, and disposal of infrastructure and equipment assets and direct land use changes.	tCO_2e

7.2.3. **The system boundary** of the carbon removal activity shall be defined across these dimensions:

a. Technical

b. Spatial or geographical

c. Temporal.

7.2.4. **The technical dimension** of the system is organized into three main unit processes as described below and represented in figure 7.1 and summarised in table 7.1:

a. **Raw material sourcing** is the process by which raw material(s) are sourced with the purpose of producing the Substrate capable of growing microalgae for carbon capture. It refers to all activities required for the extraction, transport, and pre-processing of the raw materials used in the production of Substrate for the MCFS activity. Such processes may include mining, extraction, harvesting, cutting, grinding or any other activity and input, and done prior to the arrival of the materials to the production facility, and includes packaging. For detailed requirements for raw materials, see section 3.6. This process ends with biomass supplied to the Production Facility.

b. **Substrate production** is the process by which raw materials are turned into the Substrate that will be deployed into the ocean. Such processes may include mixing, heating, cooling, cutting and any other activity or input, including quality control tests and packaging. Should the processing take place in different locations and times, that should be specified in the LCA model. This process ends with Substrate at the gate of the Production Facility, ready to be shipped for deployment.

c. **Substrate deployment** is the process by which Substrate is brought to the deployment site and added to the surface ocean for the purpose of carbon removal. This process includes transportation of any sort from the Substrate production facility to the deployment site. It may include the use of cranes, pumps, forklifts, and any other equipment necessary to carry out the deployment. This process ends with the Substrate securely deployed in an eligible site.

7.2.5. The LCA model must include a project-specific process-flow diagram that details each of the unit processes shown in figure 7.1 for the purpose of defining the scope and completeness of life cycle inventories (see also rule 7.2.4).

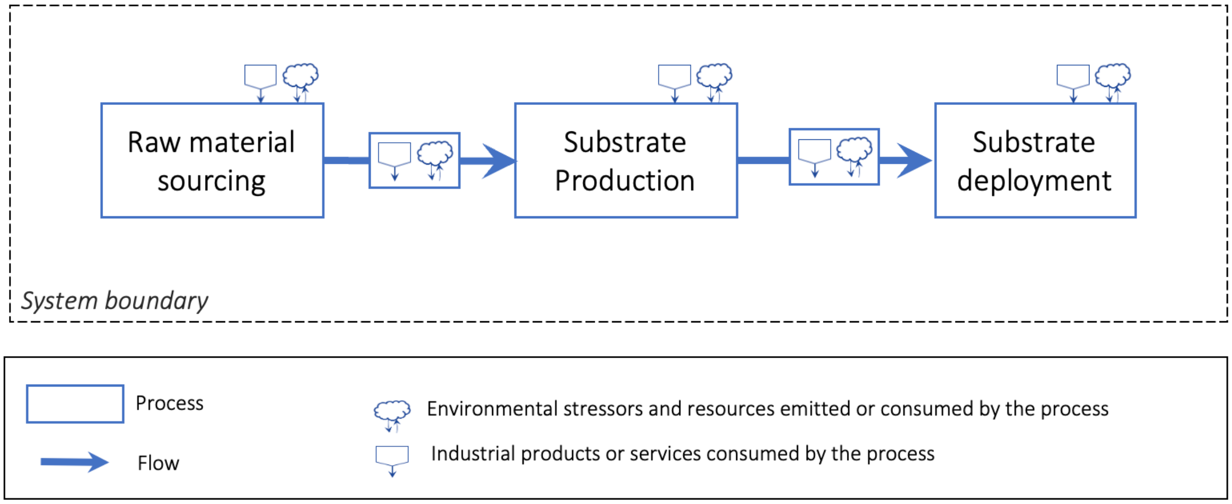

Figure 7.1. Life cycle assessment (LCA) system boundary of a Microalgae Carbon Fixation and Sinking activity.

7.2.6. The term $E_{project}$ shall not include any emissions or removals already accounted for in the terms C_{stored}, $E_{leakage}$ and C_{loss}.

7.2.7. The project emissions ($E_{project}$) shall be updated in each monitoring period with actual measured and recorded activity data such as transport distances as well as fuel, energy, and material consumption.

7.2.8. The **spatial dimension** of the LCA shall be defined in the LCA Model Description and applied to the selection of spatially-relevant emission factors and activity data. This includes the areas covered by the three unit processes, from raw material sourcing to Substrate deployment. The geolocation of the deployment and sinking site(s) shall be specified and provided as part of the Audit package in a map or a geospatial vector data (shapefile) shall be provided.

7.2.9. The **temporal dimensions** of the LCA shall be made explicit in the LCA Model and LCA Model Description, in relation to the Monitoring Period, and the specifics of each inventory (operational and embodied):

a. For **operational emissions**: the monitoring period serves as the temporal unit for calculating operational emissions. Therefore, the CO_2 Removal Supplier shall ensure that all operational emissions that occur during a monitoring period have been calculated and reported in one or several LCA calculations with explicit time boundaries. A date (year-month-day) is an acceptable description of the timing of the activity.

b. For **embodied emissions**: the CO_2 Removal Supplier shall disclose in the LCA Model Description both technical design lifetimes, as well as any useful lifetimes of the Production Facility infrastructure, because the useful lifetimes may be shorter than technical design lifetimes.

7.2.10. Changes from the process described above may occur and shall be described and justified and submitted for reassessment and project validation.

7.3. Quantification of operational emissions

Operational emissions include the greenhouse gas emissions associated with the energy used to operate facilities, machinery, or other types of equipment as well as the material inputs (e.g., biomass, water, chemicals, packaging), waste treatment, and transportation (e.g., raw material sourcing or Substrate deployment) necessary for the carbon removal activity.

7.3.1. The CO_2 Removal Supplier shall develop an operational LCI, accounting for the **operational emissions** of the three main unit processes described in rule 7.2.4.

7.3.2. The emissions from the activities covered in the operational LCI shall be measured and reported during the monitoring period following equation 7.2, and be possible to link to the amounts of Substrate produced and used during the monitoring period.

$$E_{ops} = E_{sourcing} + E_{production} + E_{deployment} \quad (7.2)$$

Where:

Variable	Description	Unit
$E_{sourcing}$	Operational lifecycle emissions associated with raw material sourcing incurred during the monitoring period.	tCO_2e

Variable	Description	Unit
$E_{production}$	Operational lifecycle emissions associated with the production of substrate incurred during the monitoring period.	tCO_2e
$E_{deployment}$	Operational lifecycle emissions associated with deployment of the substrate incurred during the monitoring period.	tCO_2e

7.3.3. For the process of **Raw Materials Sourcing** ($E_{sourcing}$), the CO_2 Removal Supplier shall account for the emissions associated with the production of raw materials, including mining and processing.

7.3.4. For the process of **Substrate Production** ($E_{production}$), the CO_2 Removal Supplier shall account for the emissions associated with production of Substrate from feedstock to a state that may be used for its final deployment (e.g., heating, cooling, mixing, chipping and packaging). In addition:

a. Emissions associated with the production of the Substrate shall be characterized on a cradle-to-gate basis.

b. The method by which emissions associated with the production and supply of the Substrate are quantified shall be described in the PDD.

c. The CO_2 Removal Supplier shall use the best available data and emission factors to quantify the above emissions. Environmental Product Descriptions (EPDs), representing the outputs of an LCA completed by a supplier(s), are eligible for this purpose.

7.3.5. For the process of **Substrate Deployment** ($E_{deployment}$), the CO_2 Removal Supplier shall account for the emissions associated with deployment of Substrate in open waters. This shall cover any material assistance in the method of sinking the resulting Substrates to the desired depth for durable and safe storage, as well as monitoring for reversal and environmental risks as defined in section 4, monitoring activities as defined in section 9, and measurement activities as defined in section 10.

7.4. Quantification of embodied emissions

Embodied emissions (E_{Emb}) represent the carbon emitted in the fabrication, construction, and E_{infra}), and in direct land-use conversion (E_{dLUC}) associated with the production facility and supporting infrastructure (when applicable).

7.4.1. The CO_2 Removal Supplier shall develop an embodied LCI, accounting for the embodied emissions of the foreground infrastructure of the Production Facility and the associated direct land use change emissions, if applicable. The LCI is subject to the cut-off criteria defined in section 7.6.

7.4.2. These embodied emissions shall be estimated subject to the accounting requirements found in rule 7.4.3 and rule 7.4.4, using the following equation:

$$E_{Emb} = E_{infra} + E_{dLUC} \tag{7.3}$$

Where:

Variable	Description	Unit
E_{Emb}	Sum of lifecycle emissions associated with infrastructure and equipment assets and direct land use changes.	tCO_2e
E_{infra}	Lifecycle emissions associated with infrastructure and equipment assets.	tCO_2e
E_{dLUC}	Lifecycle emissions associated with direct land use changes.	tCO_2e

7.4.3. Embodied emissions shall account for the life cycle emissions of infrastructure and/or equipment (E_{infra}) as follows:

a. The calculation of embodied emissions shall be cradle-to-grave, including all steps from material extraction to waste disposal, and may follow as general guidance: EN 15804+A2[59], EN 15978[60] or ISO 21930:2017.[61]

[59] EN 15804:2012+A2:2020 Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products.
[60] EN 15978:2012 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method.
[61] ISO 21930:2017 Sustainability in buildings and civil engineering works - Core rules for environmental product declarations of construction products and services.

b. Alternatively, recent monetary emission factors (e.g., kg CO_2e per USD spent) may be used as a proxy for estimating embodied emissions based on capital expenditure (CAPEX), provided that such factors are available in the countries where the facilities are built, or from other countries as proxy, if deemed sufficiently conservative. This approach may be based on an economic input-output life-cycle assessment (EIO-LCA).

c. The embodied emissions of pre-existing facilities shall not be accounted for in the project's emissions. However, additional embodied emissions associated with the retrofit and maintenance of the retrofitted facilities shall be accounted for.

d. Excluded from embodied emissions calculations are the processes for the production of vehicles and transport devices in alignment with the Global Logistics Emissions Council (GLEC) Framework v3.[62]

7.4.4. Embodied emissions shall account for direct land-use (dLUC) conversion if land use has been changed for the construction of the Production Facility e.g., from agriculture or forest land to an industrial site. To this end, the following rules shall apply:

a. dLUC emissions shall be considered and included in the LCA when the construction of the Production Facility and its supporting infrastructure entails land conversion.

b. dLUC shall be assessed relative to the land area remaining in its historical state prior to the carbon removal project (new build or retrofit).

c. dLUC shall include any loss of aboveground and belowground biogenic carbon stocks, relative to the historical state of the land. dLUC shall also include any greenhouse emissions arising during the land conversion such as emissions associated with land clearing by fire as these may include significant amounts of methane (CH_4) and dinitrogen monoxide (N_2O).

d. These emissions shall be quantified using either the default values for land conversion available in the IPCC Guidelines for National Greenhouse Gas Inventories[63] (Tier 1), country-specific values (Tier 2), or data specific to the project (Tier 3), or a jurisdictional approach when available.

e. The calculation shall be performed using the following equations:

[62] Smart Freight Centre 2023. Global Logistics Emissions Council Framework for Logistics Emissions Accounting and Reporting v3.0, revised and updated). ISBN 978-90-833629-0-8.

[63] 2006 IPCC Guidelines for National Greenhouse Gas Inventories and 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

$$E_{dLUC} = \frac{44}{12} \times CS_B - CS_P \times A + E_{Conversion} \quad (7.4)$$

where the carbon stock per unit area is defined as:

$$CS_x = C_{VEG_x} + C_{DOM_x} + SOC_x \quad (7.5)$$

Where:

Variable	Description	Unit
E_{dLUC}	Absolute direct land use change associated with the construction of infrastructure.	tCO_2e
CS_B	Carbon stock per unit area associated with the baseline land use.	tC ha^{-1}
CS_P	Carbon stock per unit area associated with the project land use.	tC ha^{-1}
A	Area of land converted.	ha
$E_{Conversion}$	Greenhouse gas emissions associated with the land use conversion activities, e.g. fuel usage for clearing the land, direct emissions from fire.	tCO_2e
CS_X	Carbon stock per unit area with the project or baseline land use, where subscript X indicates the type of land use.	tC ha^{-1}
C_{VEG_x}	Above and below ground living biomass carbon stock	tC ha^{-1}
C_{DOM_x}	Dead organic matter or litter biomass carbon stock.	tC ha^{-1}
SOC_X	Soil organic carbon stock.	tC ha^{-1}

f. The variables C_{VEG_x}, C_{DOM_x}, and SOC_X should be determined using the equations presented in volume 4 of the IPCC Guidelines for National Greenhouse Gas

Inventories[64] and the EU Commission decision on guidelines for the calculation of land carbon stocks for the purpose of Annex V to Directive 2009/28/EC[65] (see also subrule d). In addition, Puro.earth will make calculation tools and data available to the CO_2 Removal Supplier.

7.4.5. Embodied emissions shall be amortized[66] evenly over a period of time in line with its first crediting period (see rule 2.2.4), or the lifetime assumption of the Production Facility, whichever is shorter. Alternatively, the CO_2 Removal Supplier may decide to amortize all embodied emissions earlier, e.g. upfront during the first monitoring period, if requested by a third party (e.g., investor or buyer). In any case, if the project is terminated prior to complete amortization of its attributable embodied emissions, the remaining unamortized embodied emissions are considered a liability and the CO_2 Removal Supplier shall settle the outstanding embodied emissions by retiring CO_2 Removal Certificates (CORC) of similar permanence.

REMARK ON BACKGROUND INFRASTRUCTURE EMISSIONS: The rules in section 7.4 apply specifically to foreground infrastructure emissions, not background infrastructure emissions. Foreground infrastructure includes facilities built by the operator, such as MCFS production equipment and factory buildings. In contrast, background infrastructure refers to elements like the infrastructure required for electricity generation used in the process. Since background infrastructure emissions are already accounted for in the LCA emission factors—along with their own assumptions e.g. on lifetime and maintenance requirements—CO_2 Removal Suppliers do not need to modify or verify these assumptions. Background emission factors can be applied as provided.

7.5. LCA cut-off criteria

In order to simplify the development of the LCA model and the data collection process during operations, it is possible to leave out individual activities or emission sources that have an overall negligible impact on CORC quantification, following the cut-off criteria defined in this section. Cut-off criteria is here synonymous with materiality threshold. Here, this threshold for project emissions is set to 5%, which corresponds to less than 1% of the gross removal achieved in typical MCFS

64 2006 IPCC Guidelines for National Greenhouse Gas Inventories and 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

65 2010/335/ Commission Decision of 10 June 2010 on guidelines for the calculation of land carbon stocks for the purpose of Annex V to Directive 2009/28/EC (notified under document C(2010) 3751).

66 In this document, amortization is an equivalent concept to the “linear discounting approach” presented in the GHG Protocol (2011) Product Life Cycle Standard (Appendix B) and GHGP (2022) Land Sector and Removals Guidance, Part 1: Accounting and Reporting Requirements and Guidance. (Draft for pilot testing and review).

projects. Note also that cut-off criteria cannot be applied to all emissions sources, as certain sources are explicitly required to be reported regardless of their magnitude (see section 3).

7.5.1. To identify which individual activities or emission sources can be left out from an inventory model (operational or embodied), the CO_2 Removal Supplier shall first endeavor to develop a life cycle inventory that lists all possible individual activities or emission sources for each unit process (see rule 7.2.4) and type of emissions sources (e.g. energy use, material use, waste treatment, direct emissions). Supported by initial data and preliminary calculations for normal operations, the CO_2 Removal Supplier may demonstrate that certain individual activities or emission sources are expected to be negligible. Negligible is here defined as representing less than 0.5% of the total emissions of the given unit process considered, within an inventory.

7.5.2. For the individual activities or emission sources that are deemed negligible, the CO_2 Removal Supplier may decide to exclude them from the inventory, and thereby neglect their contribution to project emissions. This decision must be made explicitly and be documented motivated in the LCA Model Description, and can be challenged by the third-party auditors during Facility Audit or Output Audits alike. For example, the auditor may compare the LCI data with similar processes or available emissions databases to determine the plausibility of completeness of the proposed inventory.

7.5.3. The following elements are considered to be not relevant for the purposes of LCA modeling, and therefore do not need to be included in the LCA Model:

a. Site selection and feasibility studies, non-recurring R&D activities.

b. Staff transport (e.g., business travel and employee commuting).

c. Non-production related products, which include office furniture and supplies, IT support, and janitorial and cleaning services.

d. Monitoring activities.

7.6. Summary

7.6.1. The CO_2 Removal Supplier shall collect and organize the elements and processes that contribute to generate the overall project emissions ($E_{project}$, including both embodied and operational emissions) according to the levels of information described in table 7.1.

7.6.2. The LCA model shall be provided in a disaggregated manner and aligned with table 7.1, exhibiting the contributions of each main stage (level 1) and substage (level 2). Each sub-stage can be further divided into contributions (level 3) relevant for each project type. If a contribution is deemed not relevant or equal to 0, an explicit motivation shall be provided in accordance with the LCI cut-off criteria (see section 7.5.).

7.6.3. The CO_2 Removal Supplier shall publicly disclose the results of the LCA calculation as part of the Output Audit in the Puro Registry, at least the contributions marked with an asterisk (*) in table 7.1.

Table 7.1. Levels of contribution to the LCA calculations of the unit processes, and identification of which contributions must be made public in the Puro Registry as part of Output Audit data (marked with an asterisk, *).

Main stages **Level 1 contributions**	**Sub-stages** **Level 2 contributions**	**Further substages** **Level 3 contributions**	**Comment**
$E_{Sourcing}$	*Operational emissions of raw material sourcing	Supply (e.g., mining/production)	Either fully attributed to CORCs or partly allocated to CORCs.
$E_{Production}$	*Operational emissions of substrate production for deployment	Energy use (heat, electricity, fuel) Material use Conversion Transport of raw materials to and between production site(s)	Third-level contributions may be split in sub-stages as relevant for each supply-chain.
$E_{Deployment}$	*Embodied emissions of substrate production facility	Construction, maintenance, and disposal of infrastructure and equipment *Direct land use change (dLUC)	Maintenance can be demonstrated to be neglectable, in annual reporting.

8. Determination of Leakage

8.1. Introduction

The concept of leakage as described in the Puro Standard General Rules[67], represents a possible increase or decrease in greenhouse gas emissions or removals that is outside of the system boundaries of the activity. For the purpose of CORC quantification, only the increase in GHG emissions or decrease in carbon stocks are quantified, and the removal activity is penalized if those indirect effects are not avoided or mitigated. Net positive effects are not included in the quantification of CORCs. Addressing the risks of indirect emissions is crucial to ensuring the integrity of carbon removal interventions. By identifying possible sources of indirect emissions at the project level, the CO_2 Removal Supplier can design and implement strategies to minimize leakage and maximize the positive climate impact of their initiatives. This section defines which leakage sources are relevant to consider for MCFS activities, following the three-step approach defined in the Puro Standard General Rules:

1. Identify and characterize sources of leakage.
2. Mitigation of leakage.
3. Quantify unmitigated leakage.

8.2. Identification and characterization of leakage

Unintended consequences, such as leakage, are present in all types of activities, including CO_2 removal projects. The Core Carbon Principles (CCP) Assessment Framework and Procedure of the Integrity Council for the Voluntary Carbon Markets (ICVCM) defines four types of leakage / indirect emissions: i) activity shifting leakage, ii) ecological leakage, iii) market leakage, and iv) upstream/downstream emissions. Since upstream and downstream emissions are accounted for as part of the project emissions (see section 7), this methodology focuses on the following key sources of indirect emissions: 1) market and activity-shifting leakage (also named “Economic Leakages”), and 2) ecological leakage.

Economic leakage occurs when the carbon removal activity impacts supply or demand for emissions-intensive products (i.e., competition for resource use) or services (i.e., diversion of existing production processes), thereby increasing their production and consequently their associated emissions elsewhere (market leakage). In the context of MCFS, economic leakage may occur, primarily, if any raw material(s) used to increase carbon fixation and/or the export efficiency (whether

[67] Available in the Puro Standard document library.

a primary product or a burden-free co-product) were already used to deliver another product or service, and the competing use entails the production of additional raw material, if demand persists.

Ecological leakage arises when the activity indirectly affects emissions in connected ecosystems. In the context of MCFS, the intervention might affect the availability of nutrients in the ocean, perturbing marine food webs and by that decreasing the efficiency of the ocean's biological pump (see section 1.2).

8.2.1. For the determination of leakage, the CO_2 Removal Supplier shall base the analysis of leakage on the comparison between the baseline scenario (section 6.2) and the expected changes that the carbon removal activity may bring to the market for raw materials and services (economic leakage), or carbon stocks (ecological leakage).

8.2.2. The CO_2 Removal Supplier shall identify the key risks of leakage in all unit processes of the project (see rule 7.2.4): raw material sourcing, Substrate production, and Substrate deployment.

8.2.3. For the determination of economic leakage, the CO_2 Removal Supplier shall define if the raw materials have competing uses and/or the demand level for the service required by the carbon removal activity. The evidence should be determined through any of these studies:

a. Baseline studies;

b. Historical trends comparison;

c. Commodity market analysis,

d. Economic modeling;

e. Tracking production trends;

f. Literature benchmarks.

8.2.4. For the determination of ecological leakage, the CO_2 Removal Supplier shall require that the Environmental Impact Assessment (EIA) determines the baseline conditions and the expected changes brought in by the implementation of the carbon removal activity. In addition, the EIA shall:

a. Determine the area outside the system boundaries most likely to be impacted by the carbon removal activity.

b. Define the indicators and impact thresholds defined by the regulatory frameworks relevant to the deployment site, the most up-to-date scientific literature, and the key environmental and social risks identified in section 4.5 that could determine the leakage potential. These may include:

i. Development of hypoxia zones as oxygen depletion can occur due to decomposing biomass.

ii. Changes in food webs outside of the project boundaries as stimulating blooms in one area might reduce plankton availability elsewhere, impacting fisheries and higher trophic levels.

iii. Alterations in microbial processes that increase emissions of N_2O or CH_4.

8.2.5. After the identification of leakage, the CO_2 Removal Supplier shall first mitigate these impacts according to section 8.3, or when that is not possible, quantified according to section 8.4. Furthermore, the CO_2 Removal Supplier shall account for any unmitigated indirect emissions in the quantification of CORCs according to the rules in section 5 and section 6.

8.3. Mitigation of leakage

8.3.1. If potential ecological leakage is identified during the project design phase as part of an Environmental Impact Assessment (EIA) study, the CO_2 Removal Supplier shall ensure that the site selection process and determination of the scale of deployment minimize leakage. In addition, the CO_2 Removal Supplier shall have in place adaptive monitoring procedures for early detection of ecological or biogeochemical disruption and temporal suspension of deployment.

8.3.2. If potential economic leakage is identified during the project design phase, the CO_2 Removal Supplier shall demonstrate abundance of raw materials or services with competing uses as show that the project will not lead to diversion of production or services outside of the project boundaries.

8.3.3. Should an identified and significant leakage remain unmitigated, it shall be quantified and subtracted from the overall quantification equation as $E_{leakage}$.

8.4. Quantification of non-mitigated leakage

8.4.1. The CO_2 Removal Supplier shall quantify the total GHG emissions due to negative leakages ($E_{leakage}$) caused by negative market and/or activity shifting (E_{MAS}) and/or negative ecological leakages (E_{Eco}), based on an assessment of leakage due to the MCFS activity, in accordance with the requirements defined in section 8.3 of this methodology.

8.4.2. The term $E_{leakage}$ shall not include any emissions or removals already accounted for in the terms C_{stored}, $E_{project}$ and C_{loss}.

8.4.3. The quantification of $E_{leakage}$ shall be done using the following equation:

$$E_{leakage} = E_{MAS} + E_{Eco} \quad (8.1)$$

Where:

Variable	Description	Unit
$E_{leakage}$	Total GHG emissions due to unmitigated negative leakage resulting from the Activity.	tCO_2e
E_{MAS}	Total GHG emissions due to unmitigated negative ecological leakage resulting from the Activity.	tCO_2e
E_{Eco}	Total GHG emissions due to unmitigated negative market and/or activity-shifting effects resulting from the Activity.	tCO_2e

8.4.4. Ex-ante quantification: When ecological leakage sources are identified in the Environmental Impact Assessment (EIA) or a standalone assessment, the emissions impact shall be calculated using:

a. Methods derived from the latest version of the IPCC Guidelines for National Greenhouse Gas Inventories[68], or

b. Site-specific quantification approaches supported by robust and transparent data.

8.4.5. Post-implementation adjustments: If subsequent events reveal ecological impacts not identified during the project design phase, emissions from these impacts shall be quantified and included retroactively.

8.4.6. Leakage emissions shall be reported in units of tCO_2e, with all assumptions, data sources, and calculations documented transparently and subject to approval by the Issuing Body.

8.4.7. The CO_2 Removal Supplier shall estimate the emissions impact of market displacement by analyzing alternative uses for raw materials and capital assets (namely, machines and vessels) and quantifying any additional emissions generated due to resource competition.

8.4.8. The CO_2 Removal Supplier shall identify and quantify emissions resulting from activity shifts using lifecycle assessments, peer-reviewed studies, or equivalent methods.

8.4.9. Economic leakage due to market and activity shifting shall include the sum of all identified and quantified impacts, expressed in tCO_2e, with all assumptions, data sources, and calculations documented transparently and subject to approval by the Issuing Body.

[68] 2006 IPCC Guidelines for National Greenhouse Gas Inventories and 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

9. Monitoring requirements

9.1. Overall principles

Monitoring, measuring, and reporting the performance of carbon removal activity is essential to ensure that the requirements prescribed in this methodology have been fulfilled. Due to the complexity of the marine ecosystems, substantial risks involved with a poorly chosen or monitored deployment site and the yet evolving international and national legal frameworks related to mCDR technologies, it is paramount that the monitoring plan is designed in a robust manner, based on up-to-date scientific knowledge. As a design principle, this methodology aims to rely on —rather than duplicate — local regulations to ensure safe and operationalizable results.

In practice, the monitoring, measuring, and reporting procedures followed in this methodology are the responsibility of the CO_2 Removal Supplier. The verification of the information submitted by the CO_2 Removal Supplier is by a recognized third-party auditor. Finally, the issuance of CO_2 Removal Certificates (CORCs) as a result of the project's performance is the responsibility of the Issuing Body.

A key step in verifying the monitoring data consists of inspection of relevant evidence and corroborating calculations by the auditor. Depending on the requirement, the pieces of evidence themselves can take various forms, such as data records, permits, official documents, or other relevant information which demonstrate compliance with the requirements, and enable claims to be verified. If the auditor concludes, based on the evidence presented, that the carbon removal activity is compliant with the requirements of this methodology, the validated amount of CORCs can then be issued to the CO_2 Removal Supplier.

Note that while this section contains several overarching requirements on the data collection, monitoring, and reporting requirements concerning the MCFS activity, additional requirements on these topics are included in other sections of this methodology as well.

While the resolutions or accuracies of individual tools in the monitoring suite may vary, it is the cumulative data from the monitoring approach as a whole that yields the necessary level of detail to determine with a very high degree of certainty that the biomass is effectively stored; that groundwater, surface resources, and the environment are being protected; and that any irregularities can be detected and addressed before they escalate.

9.2. Monitoring Plan

9.2.1. The CO_2 Removal Supplier shall prepare a **Monitoring Plan** to assess the performance of the carbon removal activity by

a. ensuring the conformity of the project with the eligibility requirements (section 3);

b. monitoring environmental and social impacts in support of SDGs (section 3.10) and safeguarding against identified environmental and social risks (section 4);

c. measuring the project's carbon sequestration and GHG emissions (section 5, section 6, section 7 and section 8); and

d. verifying the permanence of the deployed Substrate and reporting of any reversal events (section 9, section 10 and section 11)

It is important to note that these goals can be achieved through several routes, and multiple monitoring techniques can often be utilized for the same parameter.

9.2.2. As different approaches might be preferred in different situations, the CO_2 Removal Supplier shall always consider site-specific needs and choose a suite of monitoring technologies that enable the verification of the quantity and location of the deployed Substrate at the levels of resolution and certainty required by the applicable local regulations and this methodology, and in accordance with the measuring requirements (see section 10), in particular, the quality control requirements presented in section 10.5.

9.2.3. The CO_2 Removal Supplier shall submit the Monitoring Plan with the project description for its validation during the Production Facility Audit, as described in the Puro Standard General Rules.[69]

9.2.4. The Monitoring Plan shall describe the procedures by which the CO_2 Removal Supplier will collect data and evidence in accordance with ISO 14064-2:2019[70] and Puro Standard requirements.[71]

9.2.5. The Monitoring Plan shall include the following:

a. purpose of monitoring (rule 9.2.1);

b. project boundaries and monitoring system diagram;

c. description of the monitoring practices based on their purpose (e.g., conformity, GHG measurement, risk assessment, etc.);

d. monitoring frequency;

e. monitoring roles and responsibilities of the project personnel;

[69] Available in the Puro Standard document library.

[70] ISO 14064-2:2019 Greenhouse gases, Part 2: Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emissions reductions or removal enhancements.

[71] Available in the Puro Standard document library.

f. data collection plan, including list of parameters and their attributes and data sources (table 10.1);

g. uncertainty assessment and measurement procedures;

h. data quality control (QC) plan;

i. information management system for record keeping and data sharing;

j. definition of threshold values for environmental and social safeguards and follow up procedures for responsible parties involved in the carbon removal activity.

9.2.6. The monitoring system shall include one or several diagrams clearly identifying all points of monitoring and measurement.

9.2.7. The monitoring system may be organized by project stage as summarized in table 9.1.

Table 9.1. Summary of required monitoring and relevant subsections organized by project stage.

Monitoring focus	Raw Material Sourcing and Substrate Production	Deployment, fixation and export phases	Post-operations phase
Eligibility requirements	Section 3.6 Requirements for substrate	Section 3.7 Requirements for the Area of Interest and deployment and sinking site Section 3.8 Requirements for phytoplankton growth and export	n/a
Environmental and social impacts	Section 3.10 Requirements for positive sustainable development goal impacts Section 4.4 Requirements for environmental and social risk assessment and management	Section 3.10 Requirements for positive sustainable development goal impacts Section 4.4 Requirements for environmental and social risk assessment and management	Section 3.10 Requirements for positive sustainable development goal impacts Section 4.4 Requirements for environmental and social risk

Monitoring focus	Raw Material Sourcing and Substrate Production	Deployment, fixation and export phases	Post-operations phase
	Section 4.5 Key environmental risks	Section 4.5 Key environmental risks	assessment and management Section 4.5 Key environmental risks
GHG emissions and carbon sequestration	Section 7 Determination of project emissions	Section 6.1. Carbon Stored Section 6.3 Carbon losses Section 7 Determination of project emissions	Section 7 Determination of project emissions
Reversal risks	n/a	n/a	Section 9.7 Monitoring for CO_2 release and reversal risks

9.2.8. Unless otherwise specified, all monitoring shall be based on activity data specific to the CO_2 Removal activity and sites of operation (e.g. Substrate sourcing, processing and deployment and sinking site).

9.2.9. The CO_2 Removal Supplier shall prepare, maintain, and comply with the validated Monitoring Plan for the MCFS activity, as further described in the following subrules:

a. The monitoring plan shall be tailored to the specific characteristics and requirements of all stages (Substrate sourcing, production and deployment) within the activity boundary.

b. The monitoring plan shall describe procedures for measuring, calculating and analyzing data and information to ensure that the deployment and sinking activities conform to expected behaviour, and that the deployed Substrates remain securely contained. To this end, the monitoring plan shall at least:

- Identify potential vulnerabilities and propose solutions to mitigate recognized vulnerabilities.
- Specify monitoring parameters and define monitoring tasks.

c. The monitoring plan shall cover activities throughout the duration of the Microalgae Carbon Fixation and Sinking activity, including:

- Baseline data gathering and deployment site characterization (pre-deployment period).
- Substrate sourcing and processing performance in accordance with the corresponding eligibility requirements.
- Performance of the deployment site during operations (deployment, sinking and post-deployment period).

9.2.10. The monitoring plan shall be periodically evaluated and updated to ensure that the monitoring practices continue to be appropriate and effective. The evaluation shall include a re-assessment of the site-specific monitoring requirements and risks. For example, updates to the monitoring plan might be necessary due to:

a. New scientific knowledge or improvements in best available technology.

b. Changes to the Production Facility that affect the activities being monitored.

c. Changes to the Puro normative framework that require an update in the monitoring activities.

d. Corrective actions requested by the Auditor.

If changes are made, the updated Monitoring Plan shall be submitted to the Issuing Body at the next Output Audit, during which it will be revalidated by the Auditor.

9.2.11. The Monitoring Plan shall describe how the CO_2 Removal Supplier plans to respond to any significant irregularities in the project performance (i.e., contingency monitoring), including the case of reversal events.

9.2.12. The performance of the parameters and items identified in the Monitoring Plan shall be reported for each monitoring period and submitted with the Output Report for verification by the third-party auditor in accordance with the Reporting requirements (section 11) of this document.

9.2.13. The CO_2 Removal Supplier shall have in place, maintain, and utilize an information system to keep records of all monitoring activities associated with the carbon removal activity. In addition:

a. These records shall include information on the parameter or process monitored (i.e. what was monitored and how), as well as the results of any measurements performed.

b. The information shall be time-stamped and quantitative, where applicable.

c. These records shall be available to the Auditor for the Production Facility Audit and Output Audits.

d. These records shall be kept for at least two years after the end of the crediting period or the last issuance of CORCs for this project activity, whatever occurs later.

9.3. Monitoring eligibility compliance

9.3.1. The CO_2 Removal Supplier shall comply with the eligibility requirements described in this Methodology and Puro Standard General Rules.[72]

9.3.2. In case of any deviation or non-conformity with the eligibility requirements and validated Production Facility design detected during a monitoring period, the CO_2 Removal Supplier shall notify the Issuing Body and develop a plan to mitigate the situation at the earliest possible and demonstrate actions to meet the eligibility requirements. The non-conformity with the eligibility requirements may:

a. Impact the verification of the Output of the Production Facility and the corresponding CORC issuance for that period.

b. Require the Issuing Body to suspend the Production Facility in accordance with the Puro Standard General Rules.[73]

9.3.3. The CO_2 Removal Supplier shall prepare a sampling plan to conform with the requirements for Substrate eligibility and characterization (section 3.6), specifically following requirements to determine the chemical composition of the Substrate prior to Substrate deployment. In particular, the CO_2 Removal Supplier shall determine:

a. The carbon content by analyzing a statistically representative sample of the Substrate by CHN analysis with combination of the Ash-Free Dry Weights (AFDW) as described in (Weil et al., 2019) and (Barillé-Boyer et al., 2003), or similar method.

b. Other chemical components associated with the environmental safeguards by determining *a priori* the ranges and/or thresholds of those chemical elements that need to be monitored to meet regulatory and safety conditions.

9.3.4. The CO_2 Removal Supplier shall ensure that the sampling plan conforms with the requirements set for Substrate (see section 3.6), to determine the structural integrity of the Substrate prior to deployment.

[72] Available in the Puro Standard document library.

[73] Ibid.

9.3.5. The CO_2 Removal Supplier shall develop a sampling plan to conform with the requirements for the deployment and sinking site eligibility and characterization (section 3.7), specifically following the requirements to assess the baseline environmental conditions prior to Substrate deployment and to detect potential environmental impacts post-deployment (see section 10.4).

9.3.6. The CO_2 Removal Supplier shall comprehensively characterize the deployment and sinking site prior to biomass deployment for two purposes:

a. To evaluate site eligibility (see section 3.7).

b. To establish the environmental conditions of the storage site prior to Substrate deployment, referred to as *environmental baseline* (see also rule 9.3.7 and table 9.2).[74]

9.3.7. The CO_2 Removal Supplier shall establish the environmental baseline included in table 9.2. in a manner which properly accounts for the oceanographic conditions at the Area of Interest as further determined in section 3.7. The CO_2 Removal Supplier may deem that certain parameters in table 9.2. are not relevant for their study site. In this case, the CO_2 Removal Supplier shall provide a justification of their omission with evidence from peer-reviewed scientific literature, pending approval by the Issuing Body.

Table 9.2. Required parameters for characterizing the deployment and sinking site prior to Substrates deployment.

Parameter	Purpose	Relevant depth
Surface water retention time	Ensure the full air-sea gas exchange	Surface
Deep water trajectory	Ensure no re-exposure occurs for at least 200 years	Closest to bottom 100 m
Seawater velocities	Assessing substrate trajectories at the fixation phase	Surface
Temperature	General site characteristic used for assessing the water column stratification, especially determining the thermocline and the mixed layer depth	Full water column

[74] While many of the required environmental baselines directly link to eligibility rules and post-deployment monitoring requirements, those that are not directly linked provide information for e.g. understanding the oceanographic conditions of the deployment and sinking site or unforeseen events.

Parameter	Purpose	Relevant depth
Salinity	General site characteristic used for assessing the water column stratification, especially determining the mixed layer depth	Full water column
Density	General site characteristic used for assessing the water column stratification, especially determining the pycnocline and the mixed layer depth	Full water column
Photosynthetic active radiation (PAR)	Characterisation of the photic zone depth	Top 200 meters
Dissolved Oxygen	Chemical composition of the seawater for environmental risks	Full water column
Chlorophyll a	Phytoplankton biomass proxy	Euphotic zone
Turbidity	Physical characteristic of seawater	Full water column
Inorganic nutrients (N, P, Si, Fe and Mn)	Chemical composition of the seawater for environmental risks	Full water column
Carbonate system, based on two measurements out of three: DIC, pH and Total Alkalinity	Chemical composition of the seawater for environmental risks	Full water column
Community composition of the main phytoplankton groups	Biological characterization of the seawater for environmental risks	Euphotic zone

9.4. Laboratory-based monitoring

While in-field measurements are necessary for monitoring the deployment and sinking site for environmental and social risks, carbon accounting, and environmental conditions at various stages of the activity, some parameters of interest for assessing changes in the deployment and sinking site may be too small to detect against natural variability, occur in irregular pulses, or be rapidly diluted out of the deployment and sinking site. Furthermore, laboratory-based experiments will also inform the predicted carbon loss due to remineralization to assess CORC evaluations (see section 6.3) with as much accuracy as possible.

9.4.1. The Prior to deployment, the CO_2 Removal Supplier shall assess the quality and variability of each batch of Substrates, at minimum for the parameters listed in rule 3.6.4. as further defined in subrules a-c:

a. All analyses shall be performed on pristine Substrates.

b. The sample size shall be at minimum 100 units of Substrate.

c. At least three replicate analyses shall be conducted.

9.4.2. Prior to deployment, the CO_2 Removal Supplier shall conduct laboratory-based incubation experiments to assess the stability of each batch of Substrate (see rule 3.6.3). The setup shall represent in-field conditions as much as possible and shall be conducted using the best peer-reviewed scientific practice available at the time of design, and detailed in the Monitoring Plan (see section 9.2).

9.4.3. The minimum requirements for the simulation of ocean conditions for testing the Substrate are as follows:

a. Shear rates or turbulence dissipation relevant databases shall be provided with accordance to the project site (Banner & Morison, 2018; Fuchs & Gerbi, 2016).

b. Orbital shaker induced turbulence - Substrate shall be inserted into a rounded topped bottle of at least 1 L SW volume and >12 mm top in diameter. The frequency (RPM) of the orbital shaker should be adjusted to simulate ocean dissipation rates as can be calculated as described in Arnott et al., 2021.

c. The dissipation rates (ε) shall be calculated using the following equation (Peters & Marrasé, 2000):

$$\varepsilon = \frac{S(d \cdot f)^3}{V} \tag{9.1}$$

Where:

Variable	Description	Unit
ε	Dissipation rate.	m^2/s^3
d	Distance the vessel travels in one oscillation.	m
f	Frequency of oscillation	Hz

Variable	Description	Unit
V	Volume of fluid	m^3
S	Surface in contact with the fluid, as derived from geometry.	m^2

d. Alternatively, the CO2 Removal Supplier may use Turbulence Induced Nano-Cosm (TINS) (Tian et al., 2018), which allows the use of higher volume tests (>10L).

e. For TINS a 50 L cubic or rounded tank with a high flow rate water circulation system shall be used.

f. TINS shall be calibrated using shear rate sensor; sensor shall be placed at the upper 2 to 10 cm (Soloviev et al., 1988). The controlled pump system shall simulate the integrated dissipation rates of typical hydrodynamic signals - shear deformation rate, vorticity, and acceleration (Fuchs & Gerbi, 2016).

9.4.4. The minimum requirements for assessing the stability of the Substrate are as follows:

a. The CO_2 Removal Supplier shall follow the criteria for minimum sample size and replicate measurements as determined in rule 9.4.1.

b. The stability of the Substrate shall be assessed based on % mass unit remaining after a minimum of 30 days in oceanic conditions by using ocean illustrative mixing set-up. Artificial SW should be used as a medium for the test and should hold similar chemical composition as of the project AOI, e.i., ionic composition and strength, conductivity/salinity and temperature. Prior to testing the SW should be filtered by a 0.22 µm standard filter to eliminate any suspended solids.

c. An orbital shaker shall be placed within a 500 ml cylindrical caped vessel. The diameter of the vessel shall be between 8 and 10 cm.

d. The orbital shaker shall be run with 100 to 160 rpm for a minimum of 30 days.

e. After 30 days, the solid that detached from the substrate, and free-suspended in the surrounding water shall be filtered using a pre-weighed 0.6 µm glass-fibre filter. The remaining solid fraction of the substrate shall be measured gravimetrically, following the method for Total Volatile and Fixed Suspended Solids (TVSS and TFSS) as defined in EPA Method 160.4.[75]

f. The fraction of detached mass shall be deducted from the original mass of Substrate (per unit) to determine the total mass.

g. Tests shall be done under simulated ocean conditions, as described in rule 9.4.3.

9.4.5. Prior to deployment, the CO_2 Removal Supplier shall conduct laboratory-based incubation experiments to assess the floatation time for each batch of Substrate (see rule 3.6.3). The incubation setup shall represent in-field conditions as much as possible and shall be conducted using the best peer-reviewed scientific practice available at the time of design, and detailed in the Monitoring Plan (see section 9.2).

9.4.6. The minimum requirements for the incubation experiments to assess the floatation time are as follows:

a. The CO_2 Removal Supplier shall follow the criteria for minimum sample size and replicate measurements as determined in rule 9.4.1.

b. The floatation time (in days) shall be defined by a binary phase of floating%, which is substrates that are in positive floating (overall density of substrate < density of SW) and is on the surface of the water inside the testing vessel. The other binary phase is 'sinked'% substrate which is determined by substrates that settle to the bottom of the vessel and have an overall substrate density higher than SW density.

c. The Substrate shall be assessed based on % mass unit float/sinked after a minimum of 30 days in oceanic conditions by using ocean illustrative mixing set-up.

d. The physical conditions simulations will be conducted using an orbital shaker and/or using a mixing tank as described in rule 9.4.3.

The incubation results shall be used as a proxy for in-field conditions and shall be utilized to inform CORC evaluations.

9.4.7. The CO_2 Removal Supplier shall evaluate the maximum growth rates of phytoplankton (rule 4.5.2) based on laboratory incubation experiments, following the requirements:

a. Incubations shall be done in HNLC seawater with natural microbial communities.

b. The duration of the experiment shall represent the in situ expected floating phase.

[75] United States Environmental Protection Agency Method 160.4: Residue, Volatile (Gravimetric, Ignition at 550C) by Muffle Furnace.

c. The light and temperature conditions shall be as representative as possible of the natural environment.

d. Macronutrients concentrations shall be maintained on the natural levels through the time of the experiment.

e. Phytoplankton community biomass growth rates on the substrates shall be calculated from the net organic matter and/or organic carbon that accumulated on the substrates over the experiment duration. ´

f. Monod constant is calculated according to Litchman et al. (2007), using the equation $K_N = 0.17V_{cell}^{0.27}$, where $V_{cell} = \frac{4}{3}\pi r_{cell}^3$ is the cell's volume, and r_{cell} is the cell's radius. The value taken is 2.5 µm as an average cell radius of phytoplankton.

9.4.8. The CO_2 Removal Supplier shall conduct laboratory-based measurements to evaluate non-sinking remineralization rate in order to calculate the sinking efficiency of the deployed Substrate ($SE_{project}$, see rule 6.1.7). These measurements shall measure the daily fractional loss of biomass on the unsunk substrate prior to sinking that occurs as a result of remineralization processes. The CO_2 Removal Supplier may utilize the respiration techniques detailed in McDonnell et al. (2015), Mislan et al. (2014), or other relevant peer reviewed techniques which calculate the remineralization rates.

9.4.9. The CO_2 Removal Supplier shall either use a half saturation constant k_{o2} of 4 µm/L or the CO_2 Removal Supplier may measure the half saturation constant with all-glass bottle incubations as described in (Gong et al., 2016; Tiano et al., 2014) or other relevant peer reviewed techniques.

9.4.10. The sinking rate shall be determined by in-situ measurements as described in rule 9.6.3. Additionally, the CO_2 Removal Supplier may utilize a sinking rate using a column to test the expected sinking rate, as determined in subrules a-f.

a. Sinking rate measurements shall be performed using measuring glass cylinders of at least 1 L in volume and at least 20 cm in length. The column has to be transparent in a way to allow continuous record of a video of the whole column maintaining good pixel resolution (≥720p).

b. The cylinder shall stand on a balanced, stable table and a camera is placed in a distance of 30 to 45 cm from it, to allow a full frame of the whole water column (from top to bottom). The camera should be stabilized to a dedicated holder to prevent any movement. Columns shall be placed against a ruler which is placed with the same distance from the camera (aligned with the column). The ruler provides a calibration of real distance against pixels.

c. Prior to substrate insertion within the column, the substrate should reach a sinking condition (density higher than water density). That can be done under a high water pressure vessel or by long exposure to SW (until reaching target density).

d. Under the sinking state, substrates are then inserted one by one to the sinking column filled with SW with similar salinity and temperature to the AOI. After substrate inserted, the camera shall record the sinking velocity from the top to the bottom of the cylinder.

e. The analysis of the videos can be done using dedicated software (e.g. DLTdv8a[76]) and video taken-frame frequency shall be not less than 30 frames per second or not lower than 1 frame every 33 milliseconds.

f. Sample size of at least 50 substrate units shall be tested.

The experimental results shall be used as a proxy for in-field conditions $SE_{project}$ and shall be utilized to inform CORC evaluations.

9.4.11. Prior to deployment, the CO_2 Removal Supplier shall conduct laboratory-based tests for leaching of micronutrients from the pristine/raw substrates. The minimum requirements for the tests are as follows:

a. Substrates shall be inserted inside a 1 L rounded bottle full of prefiltered artificial SW under diluted conditions of no more than 0.1 w/v% substrate to SW concentration.

b. Mixing shall be applied using an orbital shaker of 100 RPM for 24 hours.

c. The water will be collected for subsequent trace metal elemental analysis using ICP-OES or ICP-MS standard methods such as U.S. EPA. 1994[77], and shall be tested against the control (artificial SW with no substrate, treated under the same conditions).

d. The full mass balance of the target micronutrients (trace metals) shall be calculated using the mass difference between the control and substrate waters with the initial substrate concentrations, and shall be assessed against the total projected mass and volumes for the activity.

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[76] DLTdv digitizing tool.

[77] United States Environmental Protection Agency Method 200.7: Determination of Metals and Trace Elements in Water and Wastes by Inductively Coupled Plasma-Atomic Emission Spectrometry.

e. The trace-element content of the solid (solid/solid%; w/w%) shall be determined using elemental analysis methods as described in rule 9.4.10., following a digestion process of the substrate.

9.4.12. The CO_2 Removal Supplier may conduct laboratory-based sediment cores incubation experiments prior to Substrate deployment. The incubation experiment has two purposes: 1) to evaluate the decomposition rate of the organic matter within the water-sediment interface and 2) to evaluate the impacts of the Substrate and associated biomass on the biochemical properties at the water-sediment interface and sediment porewater. The incubation set-up shall be conducted using the best peer-reviewed scientific practice available at the time of design and detailed in the Monitoring Plan (see section 9.2). The incubation results shall be used as a proxy for in-field conditions and shall be utilized to inform CORC evaluations.

9.5. Model-based monitoring

To ensure robust, transparent, and scientifically defensible modeling of MCFS operations in the open ocean, the following requirements define the minimum standards for oceanographic modeling. These requirements apply across multiple phases of the deployment and are intended to quantify carbon fluxes, dispersal dynamics, and long-term sequestration potential with high spatial and temporal resolution.

Site-specific ocean modeling, alongside laboratory experiments and field measurements, is essential for evaluating environmental impacts and estimating carbon losses over the 200-year permanence timescale. Multiple models may be necessary at various stages of the MCFS activity, aligned with peer-reviewed scientific practices and the requirements set forth in this methodology.

General Modeling Principles

9.5.1. Modeling shall be conducted at multiple levels and spatial/temporal resolutions, focusing on the Area of Interest and its connection to regional and global circulation patterns. High-resolution models should be employed for near- and mid-field processes; broader-scale circulation may be addressed through linkage to validated regional/global datasets and models.

9.5.2. The CO_2 Removal supplier shall assess physicochemical oceanographic conditions using available physical and biogeochemical marine databases (e.g. Copernicus Marine Service database or equivalent) for the chosen Area of Interest (see section 3.7 and section 9.3). The CO_2 Removal Supplier shall demonstrate that the local and regional data is connected to global oceanographic patterns. The model selection, assumptions, configuration, and validation approach must be fully justified and subject to third-party verification.

9.5.3. All simulations shall capture site-specific project parameters, for instance the chemical and biological properties of the deployment site and the underlying storage site.

9.5.4. All simulations shall have an explicit time dimension showing the temporal changes of carbon storage at each year in order to capture any losses over time. Justification for forecasting and the integration of future climate projections (Representative Concentration Pathways (RCPs)) shall be described in the Monitoring Plan.

9.5.5. The CO_2 Removal Supplier shall quantify the uncertainty associated with modelled simulations as determined in section 10.1. The uncertainty assessment shall include estimation of errors arising from spatial and temporal heterogeneity in both the simulation itself and the in-situ measurements used to constrain and drive the model. The assessment shall be included in the Monitoring Plan.

9.5.6. The input data for all simulations shall be based on empirical data from in-situ measurements (section 9.6), supplemented as necessary by values obtained from peer-reviewed scientific literature or relevant scientific datasets (e.g., national oceanographic programs). All projects shall conduct in-situ monitoring at the deployment and sinking sites.

9.5.7. The CO_2 Removal Supplier shall utilize peer-reviewed, open-source models for all simulations. Any computer code and datasets behind the simulation shall, to the extent possible, also be available in repositories.

9.5.8. The CO_2 Removal Supplier shall describe all assumptions made within the simulation, defining the conditions under which each assumption is considered valid. All external references, including data sources, models, and supporting literature, shall be cited and their relevance to the simulation and project context thoroughly explained. All assumptions and references shall be included in the Monitoring Plan.

Modeling oceanographic conditions at the deployment and sinking site

9.5.9. The CO_2 Removal Supplier shall determine the local circulation patterns, vertical transport, and the interaction between sinking material, decomposition products (e.g., DIC), and regional water mass movements by utilizing a physical oceanographic model with relatively high spatial and temporal resolution, following the requirements in subrules a-b.

a. The modeling domain shall be sufficiently detailed to evaluate whether the decomposition products remain in deep ocean currents that are isolated from the surface for extended periods.

b. The spatial and temporal resolution, key physical parameters and all assumptions applied in forecasting ocean dynamics shall be selected based on site-specific requirements, pending approval by the Issuing Body.

9.5.10. Global ocean models shall be used to understand long-term (years to centuries) impacts of carbon sequestration. In this methodology, applicable global models have been identified for the purposes of assessing air-sea gas exchange (rule 6.1.9) and permanence (rule 6.3.4). For these models, ocean circulation dynamics have been validated across observations of mixing tracers such as temperature and salinity. They also include realistic carbon biogeochemical cycling such as air-sea gas exchange and carbonate chemistry. The approved global models have been published in peer-reviewed scientific journals, and their data is publicly available.

9.5.11. To connect local-scale processes to global ocean dynamics, a combination of regional and global models may be necessary, such as in rule 6.3.5. For such coupling of regional and global models, the appropriate outputs of the regional model shall be used as the inputs for global models, taking care to properly adjust the regional model output resolution to match the global model resolution to limit discontinuities across the two models.

9.5.12. The CO_2 Removal Supplier shall provide justification for the selection of the oceanographic models used, including its spatial and temporal resolution, key physical parameters, and all assumptions applied in forecasting ocean dynamics. This justification shall be subject to review and approval by an independent third party as part of the project verification process.

9.5.13. The CO_2 Removal Supplier shall provide a durability assessment based on peer-reviewed data of deep sea global circulation patterns, demonstrating that the modeled water masses (and associated dissolved carbon) have a residence time of at least 200 years before re-exposure to the surface ocean and atmosphere.

> **REMARK ON MODELED DURABILITY ASSESSMENT:** This methodology requires for the carbon to be effectively stored for at least 200 years. Puro.earth acknowledges that certain oceanic regions may support longer sequestration timescales, but the current ability to monitor and verify the outcome of an MCFS activity is limited. However, the CO_2 Removal Supplier may be able to demonstrate that a specific MCFS activity can reach a longer than 200-year durability.
>
> The demonstration of a longer sequestration timescale is optional and does not affect the CORC calculation but could be useful for certain stakeholders such as CORC buyers or rating agencies that would like to obtain such evidence after third-party verification.

Modeling the substrate dispersal and trajectory

9.5.14. The CO_2 Removal Supplier shall model substrate dispersion and trajectory driven by natural ocean currents to inform optimal site selection and guide the overall deployment strategy, in accordance with subrules a-g:

a. The model shall integrate both hindcast and forecast oceanographic data and include physical forcing parameters such as currents, wind, and surface waves, based on validated data products (e.g., Copernicus Marine Service or equivalent)..

b. The model shall account for the total mass, buoyancy characteristics, and residence time of the Substrate, accounting for variable floating and sinking behaviors under real ocean conditions.

c. The model shall couple physical oceanographic models with Lagrangian particle tracking to simulate three-dimensional transport, dispersion, and vertical settling of the substrate.

d. The model shall be capable of identifying optimal deployment locations, by simulating natural transport processes that deliver the substrate to the intended sinking area.

e. The model outputs shall include spatial trajectories, drift distances, and surface concentration fields throughout the fixation phase, projected at daily to weekly temporal intervals.

f. The model outputs shall include seabed deposition maps, showing the spatial distribution and concentration of the substrate at the end of the export (sinking) phase.

g. A comprehensive deployment strategy shall be developed based on model results, incorporating real-time and post-deployment monitoring data to validate predictions and enable adaptive management of future deployments.

9.5.15. The CO_2 Removal Supplier shall utilize a geo-optimization approach to enable precise placement of Substrates at designated locations, thereby enhancing the capacity of carbon fixation and minimizing potential environmental impacts. The approach shall ensure sufficient Substrate distribution, promote nutrient availability for photosynthesis, and maintain suitable MMRV operational conditions.

Site-specific biogeochemical modeling

9.5.16. The CO_2 Removal Supplier shall use a biogeochemical model that includes an NPZD (Nutrient–Phytoplankton–Zooplankton–Detritus) framework (DIC–POC–N–P mass balance module), to simulate primary production, grazing, remineralization, and nutrient uptake and carbon export. The model shall represent a vertically structured mixing layer divided into an upper productivity layer and a lower mixing layer, with appropriate exchanges between layers, the atmosphere, and the ocean interior. The model shall be used in accordance with subrules a-b.

a. The model shall be used to optimize the timing of Substrate deployment by evaluating the temporal lag between phytoplankton biomass accumulation and zooplankton grazing.

b. The model shall incorporate biogeochemistry of the applicable micronutrients, reflecting the best scientific understanding of the influence of micronutrient cycling to local productivity.

Modeling air-sea gas exchange

Modeling air-sea gas exchange of CO_2 is important in assessing the potential of atmospheric CO_2 removal by MCFS. For the purpose of this methodology, the Direct Ocean Removal (DOR) model by [C]Worthy and CarbonPlan[78] shall be used to assess the CO_2 uptake efficiency for a specific deployment and sinking site. The modeling framework for the DOR model mirrors that of Zhou et al. (2025). The DOR model uses a general circulation model coupled with an ocean biogeochemistry model that represents marine ecosystem dynamics and nutrient cycling, including the carbonate chemistry system and air-sea gas exchange. The model resolves 690 individual regions covering the global ocean. To quantify CO_2 uptake efficiency, the model was used to simulate a pulse removal of surface ocean DIC in a singular ocean region and ran forward in time for 15 years, estimating the time-evolving CO_2 uptake. This removal simulation was compared against a counterfactual baseline simulation without DIC removal to quantify the additional CO_2 uptake resulting from DOR. The DOR efficiency describes the net additional atmospheric CO_2 uptake relative to the initial DIC removal over 15 years. These pulse simulations were repeated for each region and across seasons, providing CO_2 uptake efficiency estimates specific to the deployment site and deployment season. For further details on how these efficiency values are applied for evaluating MCFS carbon storage, see Section 6.1.

[78] Chay et al. 2025 "Mapping the efficiency of direct ocean removal", CarbonPlan

9.6. Field-based Monitoring

In addition to laboratory-based experiments and model-based monitoring, field measurements are required to validate the results of incubation experiments (see section 9.4.) and to monitor for predetermined and unforeseen environmental impacts (see section 9.8.) throughout the Substrate deployment, fixation, export and post-operation stages. While the requirements set for monitoring eligibility compliance are based on peer-reviewed literature and database values, this section sets the in-situ monitoring and measurement requirements to be conducted during the operations at sea.

9.6.1. The CO_2 Removal Supplier shall conduct in-situ monitoring of water column characteristics throughout the duration of the project activity, which is divided into the following phases:

a. Pre-deployment (Baseline): Establishing natural conditions, as determined rule 9.3.7.

b. Fixation phase (Floatation): Tracking and sampling during Substrate flotation.

c. Export phase (Sinking): Monitoring and sampling during Substrate descent.

d. Post-operation (Verification): Assessing environmental impacts and reversal.

9.6.2. The CO_2 Removal Supplier shall monitor the water column characteristics at the deployment and sinking site during applicable activity phases (see rule 9.6.1) for parameters listed in table 9.3. In addition to the parameters listed, the CO_2 Removal Supplier shall identify any other relevant parameters necessary to measure at a given deployment and sinking site. The data shall be made available to the Auditor.

9.6.3. The CO_2 Removal Supplier shall monitor the water column characteristics of the control site (see rule 3.7.13) prior to deployment and after the post-operation phase, as determined in table 9.3.

Table 9.3. Required measurements for water column and Substrate properties at the deployment and sinking site determined for each activity phase (see rule 9.6.1).

Parameter	**Purpose**	**Activity stage**				
		Control Site*	**Baseline**	**Fixation**	**Export**	**Verification**
Current profile	Assessing substrate trajectories	Euphotic zone	Euphotic zone	Euphotic zone	Euphotic zone	Euphotic zone

Parameter	Purpose	Activity stage				
		Control Site*	Baseline	Fixation	Export	Verification
Temperature	General site characteristic used for assessing the water column stratification, especially determining the mixed layer depth	Full water column	Full water column	Euphotic zone	Full water column	Full water column
Salinity	General site characteristic used for assessing the water column stratification, especially determining the mixed layer depth	Full water column	Full water column	Euphotic zone	Full water column	Full water column
Dissolved Oxygen	Chemical composition of the seawater for environmental risk. At export phase used for determination of the remineralization during sinking	Full water column	Full water column	Euphotic zone	Full water column	Full water column
Chlorophyll *a*	Phytoplankton biomass proxy for background seawater monitoring	Euphotic zone	Euphotic zone	Euphotic zone	Euphotic zone	Euphotic zone

Parameter	Purpose	Activity stage				
		Control Site*	Baseline	Fixation	Export	Verification
Turbidity	Physical characteristics of the water column	Euphotic zone	Full water column	Euphotic zone	Full water column	Full water column
Inorganic nutrients (N, P, Si, Fe, Mn)	Monitoring for environmental risks	Euphotic zone	Full water column	Euphotic zone	Not required	Full water column
Carbonate system, based on two measurements out of three: DIC, pH and Total Alkalinity	Monitoring for environmental risks and pCO_2 evaluation	Euphotic zone	Full water column	Euphotic zone	Not required	Full water column
Organic carbon (TOC/ POC, DOC)	Monitoring for environmental risks	Euphotic zone	Full water column	Not required	Not required	Full water column
Total organic matter	Determination of CO_2 fixation on substrates	Euphotic zone	Substrate	Not required	Substrate sample; end of fixation phase	Not required
^{13}C carbon fixation rate	Determination of background seawater; monitoring primary productivity	Euphotic zone	Euphotic zone	Euphotic zone	Not required	Euphotic zone
Ultraphyto- plankton abundance	Assessing environmental impacts	Euphotic zone	Euphotic zone	Not required	Not required	Euphotic zone

Parameter	Purpose	Activity stage				
		Control Site*	Baseline	Fixation	Export	Verification
Microphyto-plankton abundance	Assessing environmental impacts	Euphotic zone	Euphotic zone	Not required	Not required	Euphotic zone
Phytoplankton and bacterio-plankton community composition and biodiversity	Assessing environmental impacts	Euphotic zone	Full water column	Not required	Not required	Full water column
Bacterial abundance	Assessing environmental impacts	Euphotic zone	Full water column	Not required	Not required	Full water column
CH_4, N_2O	Assessing potential greenhouse gas emissions	Surface water	Surface water	Surface water	Not required	Surface water
Algal toxins	Assessing environmental impacts	Euphotic zone	Euphotic zone	Euphotic zone	Not required	Euphotic zone
Dimethylsulfo-niopropionate (DMSP)	Monitoring for DMS precursor production by phytoplankton	Surface water	Surface water	Surface water	Not required	Surface water
Sinking rate	Acoustic tracking of sinking substrates	Not required	Not required	Not required	Euphotic zone	Not required

*Note that sampling requirements for the control site apply for both pre- and post-operations monitoring, as further determined in rule 9.3.7.

9.6.4. Unless a specific protocol is determined for any given parameter, the sampling and measurement protocols shall follow those determined by internationally recognized global ocean observing programs whenever possible. These protocols include the most up-to-date versions of:

- U.S. JGOFS Sampling and Analytical Protocols
- Hawaii Ocean Time-series (HOT) analytical methods
- GO-SHIP Repeat Hydrography Manual.[79]
- Guide to Best Practices for Ocean CO_2 Measurements.[80]
- Sampling and Sample-handling Protocols for GEOTRACES Cruises.[81]

Parameters listed in table 9.3. that do not have established protocols in the above-listed documents shall use applicable peer-reviewed scientific industry best practices and enclose details of the specific method used in the Monitoring Plan pending approval by the Issuing Body.

9.6.5. During the fixation and export phases, the CO_2 Removal Supplier shall track the floating Substrate plume using the following equipment:

a. Uncrewed Aerial Vehicles (UAVs) or drones equipped with high-definition cameras for real-time aerial imagery for tracking the Substrate plume.

b. Drifter buoys equipped with GPS tracking and environmental sensors deployed alongside the Substrates to monitor ocean surface currents and Substrate plume position.

The tracking shall be used to validate the modeled dispersal and trajectory based (see rule 9.5.14), and to optimize the determination of water column and Substrate sampling locations.

9.6.6. Water column measurements shall be taken from along the Substrate deployment area during the project activity phases (rule 9.6.1 and table 9.3.), as follows:

a. At least two full water column profile measurements for up to 5 days before first deployment during the pre-deployment phase, to establish the baseline conditions of the water column prior to Substrate deployment. The profiles shall

[79] GO-SHIP Repeat Hydrography Manual: A Collection of Expert Reports and Guidelines. IOCCP Report No. 14, IPCO Publication Series No. 134, Updated version 1.1. 2019.

[80] Dickson, A.G., Sabine, C.L. and Christian, J.R. (Eds.) 2007. Guide to Best Practices for Ocean CO_2 Measurements. PICES Special Publication 3, 191 pp.

[81] Sampling and Sample-handling Protocols for GEOTRACES Cruises (Cookbook, version 4.0, 2024).

be measured within the boundary of the deployment and sinking site. The measurements to determine the baseline conditions shall be combined with local and regional observational oceanographic data (rule 9.3.7).

b. Three surface water samples per day at least every 3 days during the Substrate fixation phase.

c. At least one water column profile of the euphotic zone at the final fixation phase prior to the export phase.

d. At least one full water column profile during the export phase.

e. At least two full water column profiles at the post-operations phase, until the water column characteristics are observed to return to baseline conditions. For further requirements, see rule 9.6.17.

9.6.7. The full water column profiles and measurements from the euphotic zone shall be obtained by deploying a CTD (Conductivity, Temperature, Depth) instrument with associated sensors for measurement of the physical characteristics as determined in table 9.3 and rosette equipped with Go-flow bottles for discrete samples collection.

a. Measurements for the full water column shall be taken from the surface (<10 m deep) to as close to the seafloor as possible.

b. Measurements from the euphotic zone shall be taken either by go-flow bottles or a pump.

9.6.8. Surface water measurements shall be taken from the top 10 meters or the top water layer within which 95 % of the deployed Substrates are floating during the fixation phase. At each measurement event, at least two randomly chosen depths within the top 10 m, at least two replicate measurements shall be taken to assess measurement error.

9.6.9. At least 10 seawater discrete samples for chemical and biological analyses (see table 9.3) shall be taken from the full water column from the surface (<10 m) to as close to the seafloor as possible. The vertical sampling resolution may vary based on the site, but the CO_2 Removal Supplier shall properly characterize the vertical variability of the site, in particular the transition of the water masses defined by temperature and salinity characteristics (see rule 3.7.9). For at least one randomly chosen measurement depth, at least two replicate measurements shall be taken to assess measurement error.

9.6.10. During the fixation and export phases (see rule 9.6.1), the CO_2 Removal Supplier shall collect Substrate samples from the Substrate deployment area as follows:

a. At least one surface net trawl per day at least every 3 days starting from day 0 during the Substrate deployment and fixation phase.

b. At least three surface net trawls during the final fixation phase prior to the export phase.

c. MOCNESS vertical tow sampling during the export phase. For further requirements, see rule 9.6.11.

9.6.11. During the export phase (rule 9.6.1.c), the CO_2 Removal Supplier shall collect samples of the Substrate and the accumulated microalgae and adjacent bacteria using MOCNESS vertical tows, conducted at multiple depth strata to assess vertical Substrate distribution. The CO_2 Removal Supplier shall determine the appropriate depth strata based on the sinking site depth (see rule 3.7.10), at a resolution of at least 200 m increments as follows:

a. 0–200 m

b. 200–400 m

c. 400–600 m

d. 600–800 m

e. 800 m–seafloor

9.6.12. The CO_2 Removal Supplier shall determine the appropriate mesh size for the nets used for the surface net trawl and MOCNESS vertical tow as follows:

a. The mesh size shall retain the Substrates while allowing any free-floating phytoplankton to pass through the mesh.

b. The appropriate mesh size shall be determined based on the size fraction distribution of the Substrate used for each batch of Substrates deployed (see rule 3.6.2).

9.6.13. The CO_2 Removal Supplier shall prepare and analyse the Substrate and the accumulated microalgae and adjacent bacteria samples for total organic carbon content (see rule 9.3.3) and other applicable parameters according to the requirements determined in rule 3.6.5. for the determination of stored carbon (see section 6.1). Blank values of initial Substrate organic carbon content (rule 9.3.3.a) shall be subtracted from the total organic carbon and the delta shall be normalised per substrate mass for carbon stored (rule 6.1.2).

9.6.14. The CO_2 Removal Supplier shall monitor the sinking of the Substrate and the accumulated microalgae and adjacent bacteria by using a dual-frequency hydroacoustic system or similar, as well as a remotely operated vehicle (ROV) equipped with high-resolution cameras to visually track the descent of the Substrates.

9.6.15. The CO_2 Removal Supplier shall determine the sinking rate of the Substrates for the determination of sinking efficiency (section 6.1). The in-situ sinking rate shall be calculated from the acoustic signal of the sinking Substrates or equivalent validated scientific equipment available at the time of operation, pending approval by the Issuing Body.

9.6.16. The CO_2 Removal Supplier may use an in-situ platform to enable sampling and substrates floating time variation (section 3.6.4). The platform shall be fulfil the following criteria:

a. The platform shall be deployed in parallel to the Substrates deployment operation and float at the deployment site for a similar duration.

b. The platform shall contain a representative amount of substrates during the full operation at deployment and sinking sites.

c. The platform shall enable in-situ seawater and plankton exchange with the surrounding environment.

9.6.17. The CO_2 Removal Supplier shall continue monitoring at the sinking site for the parameters determined in table 9.3., to specifically assess potential environmental impacts.

9.6.18. After the last deployment at a given Area of Interest, the CO_2 Removal Supplier shall create an activity closure report including relevant information of the operations at the Area of Interest. Such report may for example include:

a. Information of the entities and authorities relevant for any future activities which may be impacted by the activity.

b. Documentation and maps indicating the deployment and sinking locations for each batch of Substrates.

c. Documentation of the timeline of operations (e.g. deployment, fixation, export, post-operations phase).

d. Information on the characteristics of the the deployment and sinking site(s)

9.7. Monitoring CO_2 release and reversal

9.7.1. The CO_2 Removal Supplier shall assess the reversal risk according to the general requirements for risk assessment set in section 4.2, requirements for reversal risk assessment in section 4.3 and the Puro Standard General Rules.[82] Note, that only previously unknown or unanticipated re-emissions after issuance of CORCs are termed reversals, and separated from carbon losses which are accounted for at the time of CORC issuance (see section 6.3).

[82] Available in the Puro Standard document library.

9.7.2. The CO_2 Removal Supplier shall continue monitoring the permanence of the carbon removal activity during and after site closure (post-operations phase). In cases where the post-closure monitoring shows that the permanence of the carbon storage has been compromised, the CO_2 Removal Supplier shall follow the procedure regarding permanence and risk of reversal described in the Puro Standard General Rules, section 6.7.[83]

9.8. Monitoring for environmental and social impacts

9.8.1. For monitoring of social and environmental impacts, the CO_2 Removal Supplier shall conduct an inclusive stakeholder engagement process in accordance with the Puro Stakeholder Engagement Requirements.[84] Stakeholders may include, but are not limited to:

a. Local communities.

b. Nongovernmental organizations (NGOs).

c. Independent experts.

The result of the process shall be reported and included with the Project Description for the validation of the Production Facility. Any potential risk identified through this process shall be incorporated in the Monitoring Plan.

9.8.2. The Monitoring Plan shall include the following monitoring procedures:

a. Environmental risks including, but not limited to, the predetermined risks identified in section 4.5, in accordance with the general requirements for risk assessment (see section 4.2), requirements for environmental and social risk assessment (see section 4.4) and the environmental safeguards defined in the Puro Standard General Rules.[85]

b. The social risks identified in the Puro Stakeholder Engagement Report[86], in accordance with the general requirements for risk assessment (see section 4.2), requirements for environmental and social risk assessment (see section 4.4) and the social safeguards defined in the Puro Standard General Rules and the Puro Stakeholder Engagement Requirements.[87]

[83] Available in the Puro Standard document library.

[84] Ibid.

[85] Ibid.

[86] Ibid.

[87] Ibid.

c. The environmental and social impacts that may contribute to the Sustainable Development Goals (see section 3.10) pursued by the CO_2 Removal Supplier in accordance with the Puro Standard General Rules and Puro SDG Assessment Requirements.[88]

9.8.3. The CO_2 Removal Supplier shall monitor the environmental impacts by a combination of laboratory-based monitoring (see section 9.4), model-based monitoring (see section 9.5) and field-based monitoring (see section 9.6) for characterization of the environmental baseline at the Area of Interest (see rule 9.3.6.b), and monitor changes to the initial conditions.

9.8.4. The CO_2 Removal Supplier shall design and implement an "Ongoing feedback and grievance mechanism" as described under the Puro Stakeholder Engagement Requirements[89] to facilitate the continuous engagement between the project stakeholders for the identification and resolution of any issue or grievance associated with the carbon removal activity.

9.8.5. The CO_2 Removal Supplier shall maintain a record of the stakeholder feedback and follow-up actions, and report the status and actions associated with this process in the corresponding Output Report until its adequate resolution.

9.8.6. The CO_2 Removal Supplier shall address any grievances in accordance with the mitigation hierarchy described in section 4.2.

9.9. Monitoring for greenhouse gas accounting

9.9.1. The CO_2 Removal Supplier shall monitor project activities to collect activity data for the measuring and calculation of GHG emissions and carbon removals to determine the net carbon removal in accordance with the CORC quantification equation presented in this Methodology.

9.9.2. The CO_2 Removal Supplier should become familiar with the requirements described in section 10 and section 11 when preparing the monitoring plan. In particular, special attention should be given to the uncertainty assessment of the carbon removal activity (section 10.2).

[88] Available in the Puro Standard document library.

[89] Ibid.

10. Measuring requirements

10.1. Uncertainty Assessment of the Carbon Removal Activity

A Puro-approved Methodology is designed to minimise the uncertainty (i.e., bias) associated with conceptualisation and modelling the carbon removal activity. As improvements in knowledge become available, this Methodology will be updated. Nonetheless, The CO_2 Removal Supplier plays an important role in minimizing the uncertainty associated with the performance of carbon removal activity. This section aims at assisting in reducing and quantifying the measurement uncertainty of the activity.

10.1.1. The estimate of net carbon removal resulting from implementing Puro-approved methodologies using the corresponding CORC calculation equation shall be accurate and precise. Accuracy and precision depend on understanding the uncertainty associated with the processes and data inputs involved in quantifying GHG emissions and the resulting net carbon removal from implementing the carbon removal activity.

REMARK ON PRECISION AND ACCURACY:

Precision refers to the degree to which repeated measurements of the same variable produce consistent results. A higher precision indicates lower random error.

Accuracy refers to how closely the average of repeated measurements or predictions corresponds to the actual value of a variable. Accuracy implies the absence of systematic error or bias. This translates into the need for proper calibration of measuring equipment, the use of representative data, to name a few.

Note that precision is independent of accuracy, meaning that measurements can be precise without necessarily being accurate. For example, results can be inaccurate but precise, as illustrated in figure 10.1.(a).

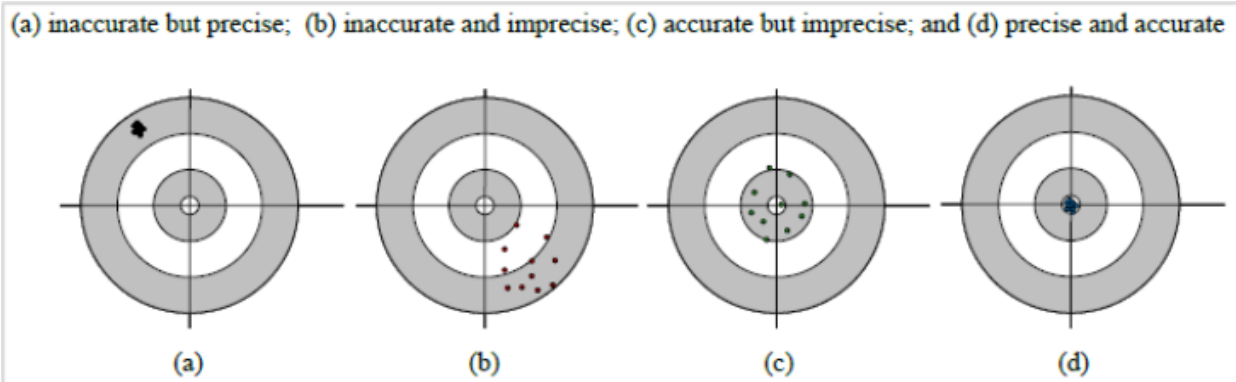

Figure 10.1. Illustration of accuracy and precision (IPCC, 2019).

10.1.2. The CO_2 Removal Supplier shall, similarly, measure accurately and precisely other parameters required by the Methodology for purposes other than GHG inventory accounting indicators as necessary. This may include indicators of toxicity levels or SDG impacts.

10.1.3. The CO_2 Removal Supplier shall perform an uncertainty assessment of the implementation of the MCFS activity to:

a. Identify the possible causes of uncertainty.

b. Establish actions to reduce that uncertainty through the design of the Production Facility (or project) and improve the accuracy and precision of the net carbon removal calculation.

10.1.4. The process of producing an uncertainty assessment follows the steps in the decision tree (see figure 10.2) and the steps described in section 10.3.

10.1.5. For the purposes of this methodology, two types of uncertainty are defined as follows:

a. Bias or systematic errors may arise from conceptual errors or an incomplete understanding of the processes involved in the CORC equation (measuring model) and its main components. Also, this may be encountered in the completeness and representativeness of the data (e.g., geographical, temporal, etc.). This type of uncertainty impacts the accuracy of the net carbon removal estimation.

b. Random errors may arise based on the system's inherent variability, measurement errors, and uncertainty obtained from expert judgment. This type of uncertainty can be estimated following the requirements set in section 10.3, and it impacts the precision of the net carbon removal estimation.

10.1.6. The CO_2 Removal Supplier shall define the actions to be taken to reduce the causes of uncertainty in implementing the carbon removal activity in the Quality Control procedures for each parameter included in data collection (see rule 10.5.3.c).

10.1.7. The CO_2 Removal Supplier may refer to the IPCC Guidelines for National Greenhouse Gas Inventories and General Guidance and Reporting for information on treating uncertainty (IPCC, 2006, 2019). Table 10.1 summarizes the broad causes of uncertainty and lists the mitigation actions under the responsibility of the CO_2 Removal Supplier.

10.1.8. The CO_2 Removal Supplier shall endeavour to identify and address all possible causes of uncertainty in the performance of the carbon removal activities.

Cause of uncertainty	Type	Mitigation actions
Lack of data	Bias	Quality Control: Expert judgement
Lack of representativeness of data	Bias	Quality Control: Pedigree matrix approach[90]
	Random errors	Quality Control: Sampling
Statistical random sampling errors	Random errors	Quality Control: Sampling
Measurement error	Bias	Quality Control: Calibration
	Random errors	Quality Control: Sampling
Misreporting	Bias	Quality Control
Data gaps	Bias and random errors	Quality Control: Statistics, Experts

Table 10.1. Causes of uncertainty (after (IPCC, 2006, 2019).

[90] GHG Protocol Quantitative Uncertainty Guidance.

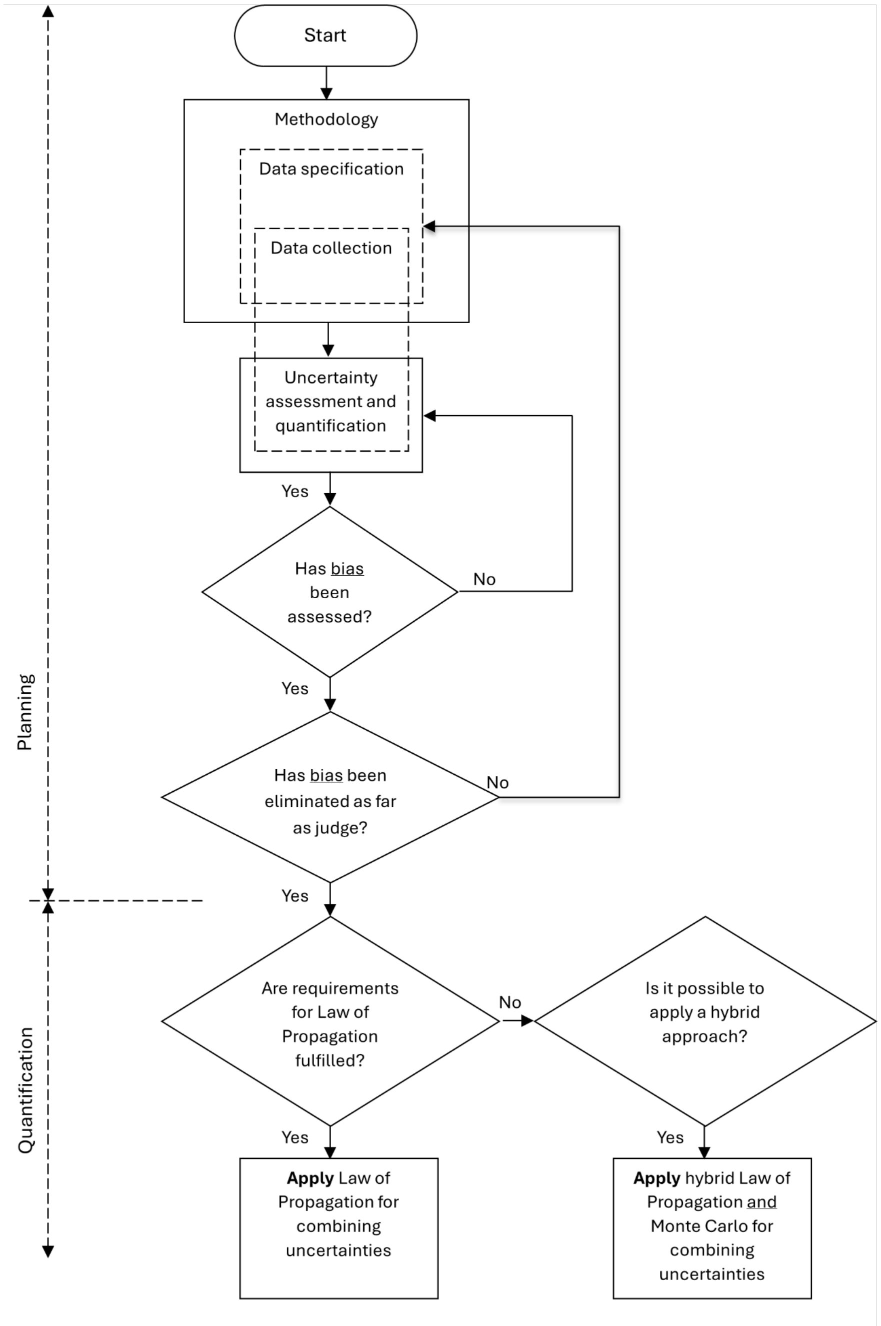

Figure 10.2. Uncertainty assessment steps and decision tree. Adapted from (IPCC, 2019), figure 3.1.A.

10.2. Data collection

10.2.1. The CO_2 Removal Supplier shall define the attributes of all the parameters described in the Monitoring Plan in accordance with table 10.2.

Table 10.2. List of required parameter attributes.

Field name	Description
ID	A unique identifier of the parameter.
Parameter	The name of the parameter.
Unit	The measurement unit of the parameter.
Value	The value of the parameter.
Equation	Reference to the equation where this parameter contributes to.
Description	A brief text describing what the parameter is about, and how it is used in calculations.
Source of data	Classify the data sourced as measured (m), estimated (e), or calculated (c) based on the definitions described in rule 10.2.2.
Monitoring frequency	The frequency of monitoring of the parameter.
QC procedures	A brief text describing how the data is obtained, via what measurements, and why the value selected is conservative considering possible error or uncertainty.
Measurement uncertainty (%)	An estimation of the random error component associated with the measurement is estimated as percentage uncertainty in the parameter.
Data archive process	How is the data archived?

Field name	Description
Time of data archive	For how long will the data be archived?
Comments	Free text comments

10.2.2. For the calculation of the net carbon removal and associated uncertainty of measurement, the sources of data and information on the carbon removal activity are:

a. **Measured.** This applies to measurements obtained via tools designed explicitly for this purpose.

b. **Estimated.** Quantified estimates based on expert judgement or based on surveys or other peer-reviewed studies. This applies to emission factors (EF) and average activity data (AD).

c. **Calculated.** Data that results from calculations based on the measured and/or estimated inputs using equations or models.

10.2.3. The International System of Units (SI) are the preferred units of measurement. Nonetheless, other unit measurement systems (e.g., the British imperial system and the United States customary system) may be used, provided the reported values are in their SI equivalent.

10.2.4. The data collection procedures shall specify the measurement and calibration methods used to collect the data in accordance with the Quality Control procedures described in this document (see section 10.5).

10.2.5. The CO_2 Removal Supplier shall develop a process for keeping a record of the data collected and submitted with the Output Report, and describe it with the data attributes (see table 10.2).

10.3. Estimation of measurement uncertainty

Knowledge of measurement uncertainty implies increased confidence in a result's validity (EURACHEM/CITAC Guide CG 4[91]). In the context of this methodology, the object of estimating measurement uncertainty is the net carbon dioxide removal based on the elements that contribute to the CORC calculation equation.

[91] EURACHEM-CITAC (2012) Quantifying Uncertainty in Analytical Measurement

10.3.1. The CO_2 Removal Supplier shall estimate the combined percentage uncertainty of the net carbon dioxide removal activity results from combining the standard uncertainty of all the parameters identified in the measurement model, the CORC equation (equation 5.1), and all its components, expanding it to cover a confidence interval of approximately 95% or two standard deviations from the mean.

10.3.2. The CO_2 Removal Supplier should refer to the ISO/IEC Guide 98 series[92] or the EURACHEM-CITAC Guide CG 4[93] for guidance on the estimation of measurement uncertainty.

10.3.3. The estimation of uncertainty shall start by determining the contributions to measurement of uncertainty from the parameters in the lowest level of the data hierarchy summarized in table 10.3 and use relevant Puro Standard guidelines and templates.[94]

Table 10.3. Hierarchy of parameters contributing to uncertainty.

Level 0 component	Level 1 contributor	Level 2 contributor	Level 3 contributor	Level 4 or more
C_{stored}	C_{fixed}	$M_{substrate}$		
		$F_{surface}$		
		C_{org}		
	$SE_{project}$	R	d_0	
			w	
			Q_{10}	
			T_0	
			T	
			k_{O2}	
			O_2	
		z_{eu}		
		z		
	AS	η_{10}		
		η_{max}		
$C_{baseline}$	$NPP_{baseline}$			
	$TE_{baseline}$			
C_{loss}	C_{stored}	C_{fixed}	$M_{substrate}$	
			$F_{surface}$	
			C_{org}	
			R	d_0

[92] ISO/IEC Guide 98 Series

[93] EURACHEM-CITAC (2012) Quantifying Uncertainty in Analytical Measurement

[94] Available in the Puro Standard document library.

Level 0 component	Level 1 contributor	Level 2 contributor	Level 3 contributor	Level 4 or more
		$SE_{project}$		w
				Q_{10}
				T_0
				T
				k_{O2}
				O_2
			z_{eu}	
			z	
		AS	η_{10}	
			η_{max}	
	F_{vent}			
$E_{project}$	E_{ops}	$E_{sourcing}$	Emission factor (EF_i) Activity data (AD_i) Allocation factor (AF_i)	
		$E_{production}$		
		$E_{deployment}$		
	E_{emb}	E_{infra}	WBLCA*	
		E_{dLUC}	CS_B	C_{VEG_B}
				C_{DOM_B}
				SOC_B
			CS_P	C_{VEG_P}
				C_{DOM_P}
				SOC_P
			A	
			$E_{Conversion}$	
$E_{leakage}$	E_{MAS}			
	E_{Eco}			

Note (*): A whole building life cycle assessment (WBLCA) for infrastructure emissions requires an extensive life cycle inventory. The CO_2 Removal Supplier should request or provide an estimated uncertainty for the whole infrastructure model.

10.3.4. The CO_2 Removal Supplier shall follow these steps to proceed with the estimation of combined percentage uncertainty of the net carbon removal:

a. The CO_2 Removal Supplier shall identify the sources of uncertainty (see rule 10.2.2) of the parameters described in table 10.3, which aims at covering the complete measuring model.

b. The CO_2 Removal Supplier shall define the uncertainty of parameters based on the source data, measured or estimated;

- The uncertainty of parameters with calculated source data shall follow the step
- Potential sources of data uncertainty are:
  - Evaluation of the dispersion of repeated measurements.
  - Previous measurement data.
  - Expert knowledge or judgement.
  - Manufacturer's specifications.
  - Data provided in calibration and other certificates.
  - Uncertainties assigned to reference data taken from peer-reviewed publications.

c. The CO_2 Removal Supplier shall start combining the percentage uncertainty of the lowest parameters in the data hierarchy described in table 10.3 to estimate the combined uncertainty of the next highest dependent parameter in the hierarchy.

d. The estimation of combined uncertainty shall use one of the two principal methods for propagating measurement uncertainty, which are:

- The law of propagation of uncertainty. This approach is described in greater detail in subrule 10.3.4.e.
- The propagation of distributions using Monte Carlo simulations. This approach is not covered in this document. For further details. Refer to ISO/IEC Guide 98-3:2008/Suppl. 1.[95]

e. The application of the law of propagation of uncertainty depends on the format of the parameter´s uncertainty, and may be combined using any of the following methods:

- In case the single parameter uncertainty is unknown, it is possible to estimate the uncertainty using the GHG Protocol guidance for "Quantitative Inventory Uncertainty"[96] This involves using the pedigree matrix approach based on qualitative indicators to compute the

[95] ISO/IEC Guide 98-3:2008 Uncertainty of measurement - Part 3: Guide to the expression of uncertainty in measurement.

[96] GHG Protocol Quantitative Uncertainty Guidance.

parameter's geometric standard deviation and propagating its uncertainty using a Taylor series expansion.

- In case the uncertainty values are presented as a percentage uncertainty, it may be combined according to IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006, 2019).

f. If applicable, the CO_2 Removal Supplier should take steps to improve the quantification of the inventory of GHG emissions and carbon removal based on the experience obtained from the previous steps with the aim of reducing the parameter uncertainty. This step should be designed in accordance with the Quality Control plan (section 10.5).

10.3.5. The CO_2 Removal Supplier shall report the combined percentage uncertainty "U" of the net removal activity in the CORC Report. The recommended reporting form follows:

$$(Result) = (X \pm U)\ (units)$$

Example: CO_2 removed: 100±0.05% tCO_2e

10.4. Sampling procedures

These sampling procedures aim to assist the CO_2 Removal Supplier in obtaining a representative sample of e.g. Substrate, water, or other products necessary to sample for demonstrating compliance with the methodology.

10.4.1. The CO_2 Removal Supplier shall determine the materials to sample according to the requirements set in this methodology.

10.4.2. If applicable, the CO_2 Removal Supplier shall prepare a complete sampling plan of the material sources (e.g., Substrate, water column samples)

a. The sampling plan for Substrate sampling may be developed in accordance with ISO 13135:2017.[97]

b. The sampling plan for water column sampling may be developed in accordance with ISO 5667-9:1992.[98]

c. In case of any other relevant material the CO_2 Removal Supplier shall provide evidence of following a relevant standard or a guideline.

[97] ISO 18135:2017 Solid Biofuels - Sampling.

[98] ISO 5667-9:1992 Water Quality - Sampling. Part 9: Guidance on sampling from marine waters.

10.4.3. The sampling plan shall clearly state the objective of sampling, such as determining the eligibility of the storage site or monitoring for environmental impacts. The sampling plan shall include detailed protocols for sample collection for all relevant parameters listed in table 9.3.

10.4.4. In the case of a new Substrate or a Substrate supplier, the existing sampling plan shall be checked and updated accordingly, or a new full sampling plan shall be prepared. The new sampling plan shall be incorporated with the corresponding Output Report for verification by the third-party auditor.

10.4.5. A sampling plan shall be used to prepare the corresponding sampling certificate. The certificate shall be made available to the third-party auditor.

10.5. Quality control (QC) system and procedures

10.5.1. The CO_2 Removal Supplier shall develop a quality control (QC) system that includes procedures to measure and control the quality of the GHG inventory for the calculation of the net carbon removal that will be included in the Output Report. The QC system is designed to:

a. Ensure the data is presented in accordance with the principles described under ISO 14064-2103, namely, relevance, completeness, consistency, accuracy, transparency, and conservativeness.

b. Identify and address errors and omissions.

c. Document and archive all inventory material and records in accordance with rule 11.1.5.

10.5.2. Information provided by the CO_2 Removal Supplier shall be verified by a third-party Auditor, who will provide the quality assurance (QA) of the performance of the carbon removal activity in accordance with the Puro Standard General Rules[99] and the requirements set in this methodology.

10.5.3. The CO_2 Removal Supplier shall provide a quality control (QC) plan, which is to be included in the Monitoring Plan. The plan shall at minimum:

a. Identify the parties involved in coordinating the implementation of the quality control procedures.

b. Define the quality control procedures.

[99] Available in the Puro Standard document library.

c. Ensure availability and access to information on activity data and emission factors, including data quality and measurement uncertainty in accordance with the requirements for data collection (section 10.3).

d. Ensure confidentiality of inventory and source category information, when required.

e. Define requirements for archiving information.

f. Define frequency of QC checks on different parts of the inventory.

10.5.4. The CO_2 Removal Supplier should consider the feedback from the verification of the Output Report to:

a. Improve the estimates of emissions and/or removals.

b. Reassess of inventory compilation processes and uncertainty estimates, when required.

10.5.5. The QC procedures shall include at minimum the calibration of the measuring equipment.

a. All measurement devices shall be installed, operated and calibrated according to the device manufacturer's specifications or according to an appropriate industry consensus standard.

b. All measurement devices shall be calibrated to an accuracy of at least 5% (i.e. the calibration error of any measurement device shall not exceed 5%). Calibration records shall be made available for third-party verification.

c. This requirement does not apply to energy (heat, electricity, fuel) billing meters, provided that the energy supplier and the CO_2 Removal Supplier do not have any common owners and are not owned by subsidiaries or affiliates of the same company.

11. Reporting requirements

The Output Report is a structured compilation of documents and data, based on templates provided by Puro.earth and other free-format documents and data. It can also contain updated documents from the Facility Audit, such as an updated monitoring plan, if changes to operations have taken place and need to be re-validated, as allowed under certain circumstances by the methodology. The Output Report is transmitted by the Issuing Body, after review, to the Auditor and serves as a basis for the performance verifications.

11.1.1. The CO_2 Removal Supplier shall prepare and make available an Output Report to provide evidence of the Production Facility performance for the monitoring period covering the scope of monitoring as described in rule 9.2.1 and demonstrates conformity of the Microalgae Carbon Fixation and Sinking activity with the requirements of this methodology, as well as the Puro Standard General Rules[100] and other Standard Requirements.[101]

11.1.2. The CO_2 Removal Supplier must, in conformity with the Puro Standard General Rules[102], submit the Output Report within the allowed timelines, promptly report any delays to the Issuing Body.

11.1.3. In case any non-conformity with the eligibility requirements and the validated design of the Production Facility is detected during a monitoring period, the CO_2 Removal Supplier shall:

a. Notify promptly the Issuing Body after detection of the situation.

b. Develop a plan to solve the situation at the earliest possible.

c. Demonstrate to the Issuing Body actions have been taken to resolve the situation at the earliest possible.

d. Keep records and evidence of the resolution available for the next Output Audit.

11.1.4. Any delays in reporting (rule 11.1.2) or non-conformity situations (rule 11.1.3) may:

a. Impact the verification of the Output of the Production Facility and the corresponding CORC issuance for that period.

b. Require the Issuing Body to suspend the Production Facility in accordance with the Puro Standard General Rules.

[100] Available in the Puro Standard document library.

[101] Ibid.

[102] Ibid.

11.1.5. The Output Report shall include supporting documented evidence for each monitoring period described in the Monitoring Plan, including the following:

a. **Production Facility and Supplier Information**: details as presented in the Project Description document, including the crediting period, type of carbon removal activity, and the methodology version followed.

b. **Report Details**: Date of the report and the monitoring period covered.

c. **CORC Report**: a CORC Report with supporting detailed calculations and evidence, based on the template provided by Puro.earth, and including the Public Summary for in the Public Registry. The CORC Report contains the total amount of CORCs the CO_2 Removal Supplier is reporting for verification.

d. **Uncertainty Statement**: describe uncertainties in the quantification, their impact on the CORC Report, and measures taken to minimize misrepresentation.

e. **Stakeholder engagement**: records of ongoing feedback and grievance provided by stakeholders and the state of resolution of any outstanding issues.

f. **Environmental and social impacts**: document any environmental and social impacts that may have occurred during the monitoring period and the corresponding actions taken by the CO_2 Removal Supplier to address the needs of the situation.

g. **Changes to Facility Audit documentation**: updated documents from the Facility Audit, such as an updated monitoring plan, if changes to operations have taken place during the monitoring period.

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