Enhanced Rock Weathering

Methodology for CO_2 Removal

Edition 2025 v.0.9

Puro Standard

September, 2025

Draft for public consultation

Document name	Enhanced Rock Weathering
Document version	Edition 2025 v.0.9 (draft)
Date of release	September 8th, 2025
Applicable methodologies	Enhanced Rock Weathering, Edition 2025 (pending approval)

DRAFT FOR PUBLIC CONSULTATION

Enhanced Rock Weathering
Methodology for CO_2 Removal

Edition 2025 v. 0.9

Puro Standard
September, 2025

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.

Application site – a *plot* or a collection of geographically proximate *plots* to which weathering material is applied and that are similar in relevant parameters (see section 11.1) and grouped together for monitoring purposes.

Base cation – a positively charged alkali metal or alkaline earth metal ion. For the purposes of this methodology, the base cations are defined as sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}).

Bicarbonate – a widely used name for hydrogencarbonate, a polyatomic anion with the chemical formula HCO_3^-. Bicarbonate can be formed via deprotonation of carbonic acid during weathering.

Carbonate – a polyatomic anion with the chemical formula CO_3^{2-}. The word ‘carbonate’ can also refer to solid carbonate minerals (See *Solid carbonates/ carbonate minerals)*, which in this text are consistently referenced as such to distinguish them from the carbonate ions.

Control site – a *plot* or a collection of geographically proximate *plots* that are similar in relevant parameters (see section 11.1) and grouped together for monitoring purposes to which no weathering material is applied, but which is otherwise managed and monitored under the same conditions as the *application site*. The control site is used as a reference to assess baseline environmental parameters and isolate the effects of the Enhanced Rock Weathering activity.

CO_2 Removal Supplier – the party authorized to represent the end-to-end supply chain of the enhanced rock weathering activity.

Deployment Period – The time interval beginning with an application of weathering material at the Field Site and ending either with the subsequent application of weathering material or with the end of the crediting period. A deployment period may contain one or more monitoring periods used for carbon removal accounting and CORC issuance.

Eligible activity – an activity capable of storing carbon dioxide in the form of *carbonate* or *bicarbonate* ions or *solid carbonate minerals* via the application of *weathering material* to one or several *application sites*.

Enhanced Rock Weathering – a CO_2 removal method where the application of a *weathering material* to soils results in the storage of carbon dioxide in the form of *carbonate* or *bicarbonate* ions or *solid carbonate minerals*.

Evaluation Area – the subset of the *application site* area that is being monitored for C_{stored} quantification and validation more densely than the rest of the *application site*.

Feedstock – see *Weathering material*.

Field site – a field site equals the set of all *application* and *control sites* within a Production Facility.

Homogeneous stratum – a defined area within the Field site that exhibits uniform characteristics relevant to ERW implementation and monitoring as further defined in this methodology.

Model (process-based) – process-based models for ERW can be described as a set of functions implemented in computer software that represent biogeochemical processes and that are utilized to make a prediction related to the weathering reactions and the associated carbon dioxide removal depending on a certain number of input parameters. Beyond that, this methodology uses the word model in a wider sense that includes also the subsequent data analysis and interpretation of the results by experts. Process-based models are distinguished from statistical models (e.g., linear regressions, bayesian models).

Plot – an individual field (small continuous piece of land) used primarily for growing agricultural crops.

Potentially toxic elements (PTEs) – any substances that are or can reasonably be thought to be present in the weathering material in concentrations high enough to be harmful to living organisms, including plants, animals, and humans. In particular, PTEs relevant to this methodology include but are not limited to heavy metals, asbestiform minerals, and radioactive minerals.

Production facility – the ensemble of physical assets, infrastructure, and operational processes necessary to perform the end-to-end activities associated with an Enhanced Rock Weathering activity, and subject to the Production Facility Audit as per the terminology defined in the Puro Standard General Rules.[1] See section 2.2 for a detailed description.

Simulation – an enhanced rock weathering *model* or the prediction produced by the *model*. See *Model*.

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.

Solid carbonates/ carbonate minerals – solid compounds composed primarily of carbonate ions (CO_3^{2-}) and divalent cations such as Ca^{2+} (as in calcium carbonate, $CaCO_3$) and/or Mg^{2+} (as in magnesium carbonate, $MgCO_3$).

Weathering material – the material being spread to an *application site*, capable of facilitating carbon dioxide storage in the form of *carbonate* or *bicarbonate* ions or *solid carbonate minerals* via chemical reactions. The weathering material can consist of rocks or other suitable materials such as alkaline waste products (e.g. slag or cement kiln dust). Used interchangeably with *Feedstock*.

Weathering signal – an empirical measurement (such as the depletion of weathering reagents or the accumulation of reaction products in time) that serves as a direct or proxy indicator of active mineral

---

[1] Available in the Puro Standard document library.

weathering processes in soils. Reliable sequestration quantification approaches often rely on quantitative and qualitative weathering signals measured over a period of time.

Acronyms

AAS – Atomic Absorption Spectroscopy

CDR – Carbon Dioxide Removal

CEC – cation exchange capacity

CORC – CO_2 Removal Certificate

DIC – Dissolved Inorganic Carbon

DM – Dry matter

DP – Deployment Period

ERA – Environmental Risk Assessment

ERW – Enhanced Rock Weathering

FFZ – Far-field zone

GHG – Greenhouse gas

ICP-MS – Inductively Coupled Plasma Mass Spectrometry

ICP-OES – Inductively Coupled Plasma Optical Emission Spectrometry

IPCC – Intergovernmental Panel of Climate Change

LCA – Life Cycle Assessment

MP – Monitoring Period

NFZ – Near-field zone

PTE – Potentially Toxic Element

RMSE – Root Mean Square Error

SIC – Soil Inorganic Carbon

SOC – Soil Organic Carbon

tCO_2e – tonnes of CO_2 equivalents

XRD – X-ray diffraction

Chemical species

Ca^{2+} – Calcium cation

$CaCO_3$ – Calcium carbonate

CH_4 – Methane

Cl^- – Chloride ion

CO_2 – Carbon dioxide

CO_3^{2-} – Carbonate ion

H_2CO_3 – Carbonic acid

HF – Hydrofluoric acid

H_2O – Water

H_2SO_4 – Sulfuric acid

HCO_3^- – Hydrogen carbonate, also known as bicarbonate

HNO_3 – Nitric acid

K^+ – Potassium cation

Mg^{2+} – Magnesium cation

N_2O – Dinitrogen monoxide, also known as nitrous oxide

Na^+ – Sodium cation

NO_3^- – Nitrate

PO_4^{3-} – Phosphate

SO_2 – Sulfur dioxide

SO_4^{2-} – Sulfate

SO_x – Sulfur oxides in general

Minerals

Anorthite – $CaAl_2Si_2O_8$ (calcium aluminosilicate feldspar)

Albite – $NaAlSi_3O_8$ (sodium aluminosilicate feldspar)

Kaolinite – $Al_2Si_2O_5(OH)_4$ (aluminum silicate hydroxide clay)

Wollastonite – $CaSiO_3$ (calcium metasilicate)

Calcite – $CaCO_3$ (calcium carbonate)

Olivine – $(Mg,Fe)_2SiO_4$ (magnesium iron silicate)

Note to the reader

> **REMARK:** This methodology provides general information as well as actual requirements that 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 example below.
>
> 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 achieved through the enhancement of natural chemical weathering processes in soil. By applying eligible weathering materials to terrestrial environments, atmospheric CO_2 is safely sequestered as carbonate minerals in soil or the dissolved inorganic carbon (DIC) species bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) in the ocean, where the carbon is safe from re-emission to the atmosphere with oceanic residence times of ~10^5 years (Lord et al., 2016; Renforth & Henderson, 2017). These timescales support the claim that ERW can achieve permanence exceeding 1000 years.

In this methodology, Enhanced Rock Weathering (ERW) refers to the overall process of applying finely ground weathering material (e.g., natural silicate- or carbonate-rich rocks or artificial materials such as slags, mine tailings or other alkaline industrial waste materials) to land surfaces such as croplands, grasslands, or other suitable terrestrial environments, for the purpose of durable CO_2 removal.

In broad terms, the scope of this methodology includes the following fundamental components: sourcing, processing, transportation, and application of eligible weathering material, monitoring of weathering rates and CO_2 removal, and verification of long-term carbon sequestration (see also figure 7.1).

1.2. Mechanism for CO_2 Sequestration

Natural and enhanced weathering

Rock weathering is a natural process estimated to sequester ~1 Gt of atmospheric CO_2 per year (Ciais et al., 2013; Strefler et al., 2018). In the weathering process, atmospheric CO_2 dissolves in water (e.g. rain droplets or river water), forming carbonic acid (H_2CO_3) (see figure 1.1 and eq. 1.1). This weak acid reacts with alkaline minerals in silicate and carbonate rocks, generating stable bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions from the carbonic acid while releasing base cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) from the mineral. The resulting dissolved inorganic carbon (DIC) species either precipitate as minerals in the soil or are transported via rivers to the ocean, where they may remain in solution over time scales of millennia (Lord et al., 2016). In ERW, the natural weathering process is accelerated by spreading finely ground rocks or other suitable feedstock materials onto soils (for further details, see section 1.4).

Weathering reactions

When atmospheric CO_2 dissolves in water, it first undergoes a sequence of reactions that begins with its hydration to form carbonic acid (H_2CO_3). Carbonic acid then dissociates into bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions, releasing protons (H^+) in the process (see eq. 1.1). This reaction lowers the pH and enables further interaction with alkaline minerals.

$$CO_{2\,(aq)} + H_2O_{(l)} \leftrightharpoons H_2CO_{3\,(aq)} \leftrightharpoons H^+_{(aq)} + HCO_3^-{}_{(aq)} \leftrightharpoons 2H^+_{(aq)} + CO_3^{2-}{}_{(aq)} \tag{1.1}$$

Rock weathering occurs when carbonic acid, formed from dissolved CO_2, reacts with minerals such as calcium or magnesium silicates. This process releases base cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and forms bicarbonate ions, increasing the total alkalinity of the system. The reaction follows the general pattern:

$$\text{mineral} + \text{aqueous } CO_2 \rightarrow \text{cations} + \text{bicarbonate} + \text{secondary silicates/clays} \tag{1.2}$$

For example, the weathering of the calcium-rich feldspar anorthite ($CaAl_2Si_2O_8$) proceeds as follows:

$$CaAl_2Si_2O_{8\ (s)} + \mathbf{2\ CO_2}_{\ (aq)} + 3\ H_2O_{\ (l)} \rightarrow \mathbf{Ca^{2+}}_{\ (aq)} + \mathbf{2\ HCO_3^-}_{\ (aq)} + Al_2Si_2O_5(OH)_{4\ (s)} \tag{1.3}$$

In this reaction, the release of one mole of Ca^{2+} is accompanied by the formation of two moles of bicarbonate, each contributing one equivalent of alkalinity.[2] If the CO_2 involved originates from the atmosphere, this results in the net removal of two moles of atmospheric CO_2 per mole of Ca^{2+} released. The reactions for CO_2 hydration/dissociation and mineral dissolution occur in parallel, together defining the weathering process.

It is important to recognize that the net carbon removal resulting from the weathering reactions depends on the type of mineral weathered. For instance, the dissolution of calcite results in only *one* mole of atmospheric CO_2 removed per mole of Ca^{2+} released and mole of $CaCO_3$ dissolved (compared to the *two* moles of CO_2 in the anorthite example above in eq. 1.3), thus making calcite weathering 50% less efficient than silicate-mineral weathering in terms of net CO_2 sequestration per mole of Ca^{2+} released:

$$CaCO_{3\ (s)} + \mathbf{CO_2}_{\ (aq)} + H_2O_{\ (l)} \rightarrow \mathbf{Ca^{2+}}_{\ (aq)} + \mathbf{2\ HCO_3^-}_{\ (aq)} \tag{1.4}$$

However, note that in addition to this stoichiometric CO_2 sequestration potential, the overall suitability of a particular feedstock for ERW depends on several other factors as well, such as the reaction rate and environmental safety of the material (see section 4.5). For example, the dissolution rate of calcite is orders of magnitude faster compared to that of anorthite (White et al., 1999).

1.3. Storage of sequestered carbon

Fate of the weathering products and storage permanence

As summarized above (see equation 1.2 and associated text), the weathering process releases base cations, bicarbonate and secondary minerals into the soil system. The durable storage of atmospheric CO_2 comes from two primary pathways. One pathway involves the precipitation of solid carbonate minerals, particularly pedogenic carbonates formed within the soil matrix (see equation 1.5). The permanence of this form of storage is highly site-specific, influenced by factors such as soil pH, moisture, mineral saturation states, and biological activity, where the main carbon storage loss comes from the dissolution of the carbonate mineral and the export of weathering products. It is by far the

---

[2] Note that under certain conditions such as high pH, elevated concentrations of Ca^{2+} and HCO_3^-, and limited water movement, calcium and bicarbonate can react to form solid calcium carbonate ($CaCO_3$), a process known as secondary carbonate formation. This may reduce the net CO_2 removal if the associated CO_2 is re-released during precipitation.

less common pathway in ERW and is only feasible and quantitatively viable under certain soil conditions (see below).

The second and main ERW pathway involves the storage of carbon in dissolved ionic form, with bicarbonate being the dominant and most stable form under typical environmental conditions. In the ocean, bicarbonate can persist for millennia.

The way of the ERW products (bicarbonate and associated cations) to their ocean storage site begins after their release into soil pore water, dissolution products begin moving through the terrestrial environment. Preventing or delaying this, base cations may be taken up by plants, adsorbed onto cation exchange sites on soil particles or organic matter, or incorporated into secondary minerals (see section 1.6). Over time, the dissolved ERW products undergo leaching (i.e., are carried downward through the soil profile by soil water) and enter the groundwater from where they may be transported via streams and rivers to the ocean (Gastmans et al., 2016).

Beyond their role in carbon storage, dissolution products also provide practical means of tracking and quantifying ERW. The concentrations of base cations (e.g., Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}), DIC or alkalinity can serve as proxies for the extent and rate of mineral weathering. Because these solutes are conserved during transport, their presence and ratios in soil solutions, river chemistry, and receiving water bodies provide measurable indicators of both weathering progress and the fate of sequestered carbon (Mills et al., 2024).

Near-Field and Far-Field Zones

This methodology adopts the convention of conceptually dividing the spatial domain of ERW into two non-overlapping spatial zones: the **near-field zone (NFZ)** and the **far-field zone (FFZ)** (Mills et al., 2024). The NFZ corresponds to the upper soil layer where the enhanced weathering of rock feedstocks is empirically quantified (see figure 1.1). The FFZ includes deeper soil layers, groundwater, rivers, and the ocean.

Conceptually, the NFZ depth is the point below which captured CO_2 is safe from re-emission to the atmosphere, i.e., the depth where even diffusive exchange between atmospheric and soil-based CO_2 becomes negligible (Mills et al., 2024). In practice, however, this strict definition is unworkable because CO_2 exchange depends on spatially heterogeneous and temporally dynamic multiphase processes that cannot be generalized and can extend one or more meters below the surface. Therefore, this methodology defines the operational NFZ depth pragmatically and encompasses the portion of the soil profile where the CO_2 Removal Supplier must monitor and measure the enhanced weathering reaction (see section 11.2: sampling depth) to quantify C_{stored}, $C_{baseline}$, and the C_{loss} components (eq. 5.1): non-carbonic acid weathering, plant uptake of major cations, cation adsorption to soil particles, secondary carbonate mineral formation, and secondary silicate mineral formation (section 1.6, section 6.2). Loss pathways occurring in the FFZ include those associated with carbonate system re-equilibration and carbonate mineral precipitation in surface freshwater or marine systems.

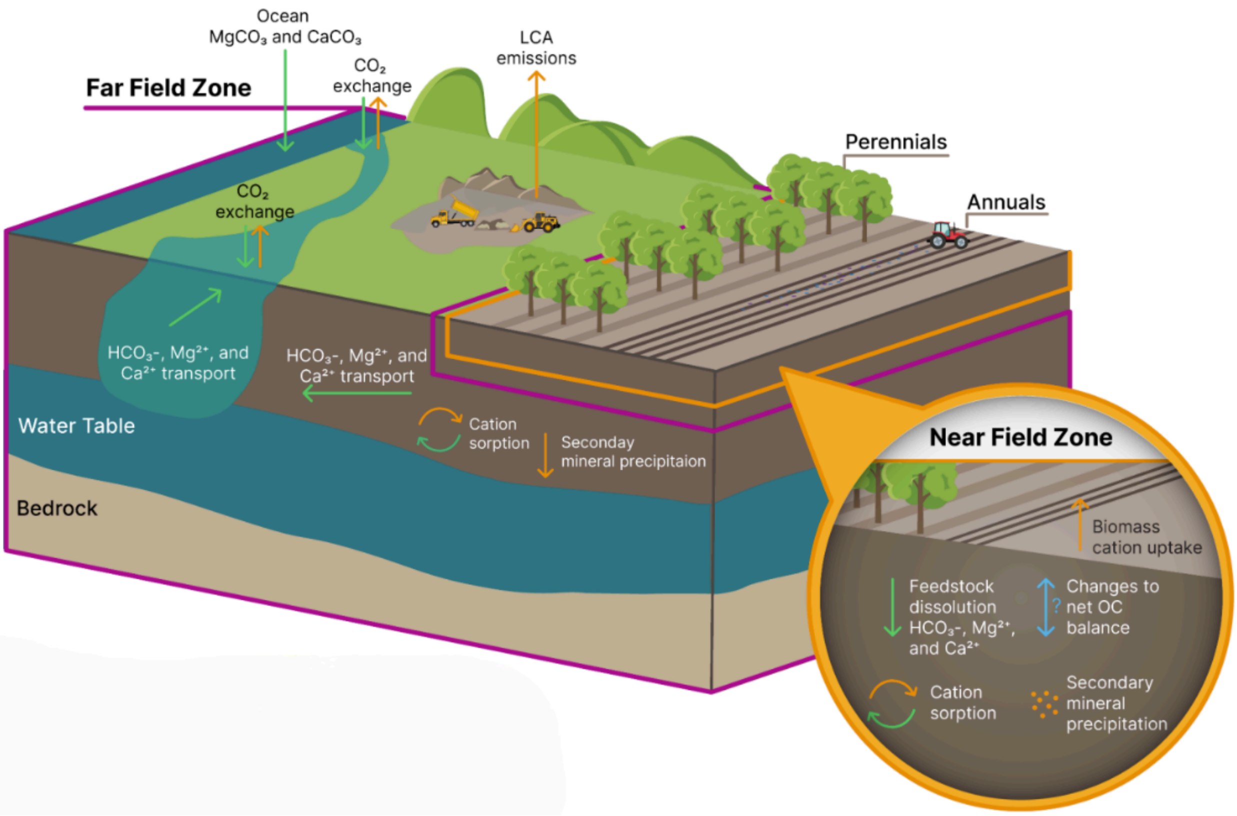

Figure 1.1. Diagram adapted from Mills et al. (2024) showing the Near-Field Zone (orange frame), where feedstock weathering occurs and fluxes of weathering products are measured, and the Far-Field Zone (purple frame), where weathering products move toward long-term storage. Green arrows show the fluxes of weathering products generated from ERW. Orange arrows indicate loss pathways and emissions. Blue arrow indicates changes to the net organic carbon due to the variable responses of SOC to alkaline feedstock addition.

Secondary (pedogenic) carbonate mineral formation

Under certain soil conditions such as carbonate oversaturation, high pH, and low soil moisture, carbonate minerals, especially calcium carbonates, may precipitate in the soil. In the ERW context, these pedogenic (formed within the soil matrix) carbonates are typically referred to as secondary carbonates if they are produced as a result of silicate weathering and are not simply present in the added rock. Increasing soil alkalinity caused by ERW may promote pedogenic carbonate precipitation (Kantzas et al., 2022). Secondary carbonate formation has been observed in several pot-based trials and field studies on ERW (Haque et al., 2020; Manning et al., 2013) and can be described by the following general formulation:

$$Ca^{2+}_{(aq)} + 2\ HCO_3^{-}{}_{(aq)} \longrightarrow CaCO_{3\ (s)} + \mathbf{CO_2}_{\ (aq)} + H_2O_{(l)} \tag{1.5}$$

This reaction results in the release of one mole of CO_2 for every mole of calcium carbonate precipitated, thereby reducing the net carbon capture from silicate-rich feedstock weathering and erasing any previous carbon capture from carbonate mineral dissolution. This “lost” CO_2 could potentially be re-captured if the precipitated $CaCO_3$ undergoes carbonic acid weathering. Alternatively, if the $CaCO_3$ dissolves via non-carbonic acid pathways, both moles of sequestered CO_2 could eventually be emitted back to the atmosphere (Hamilton et al., 2007).

Carbonate mineral formation in soils can be measured using methods for quantifying soil inorganic carbon (SIC), including calcimetry and thermogravimetric analysis, as well as using stable and radioactive isotope techniques to determine the source and age of the carbonate minerals, respectively (section 11.2).

Aqueous phase composition and the role of pH in ERW

The role of pH in ERW is complex (Haque et al., 2023). At the near-neutral pH typical of rivers (~pH 7), most dissolved inorganic carbon (DIC) exists in the form of bicarbonate (see figure 1.2). While the optimal pH varies by mineral type, silicate weathering rates generally increase at lower pH. However, low pH (<6) shifts DIC speciation toward CO_2, which undermines ERW's goal of storing carbon as bicarbonate. A **Bjerrum plot** (figure 1.2) illustrates the carbonate speciation as a function of pH in soil porewater. At low pH (below ~6.3), most DIC is in the form of CO_2, whereas at near-neutral pH (pH 7-9, typical of river water) it is HCO_3^- which dominates, and at higher pH, the CO_3^{2-} ion gains importance. However, at high pCO_2 and high DIC, even mildly acidic to neutral pH (~5.5 to 7.5) can lead to CO_2 oversaturation. Oversaturation can lead to CO_2 degassing when the partial pressure of CO_2 (pCO_2) in pore water is higher than in the surrounding pore air. If the soil column is sufficiently permeable, this CO_2 can escape to the atmosphere and (partially) negate any CDR efforts. It is also important to note that the soil system pH can change with degassing. However, if the buffer capacity of the soil is high, the pH might not change significantly. Factors that increase the soil buffer capacity include the presence of alkaline materials, high cation exchange capacity (CEC) and base saturation, as well as the presence of humic and fulvic acids.

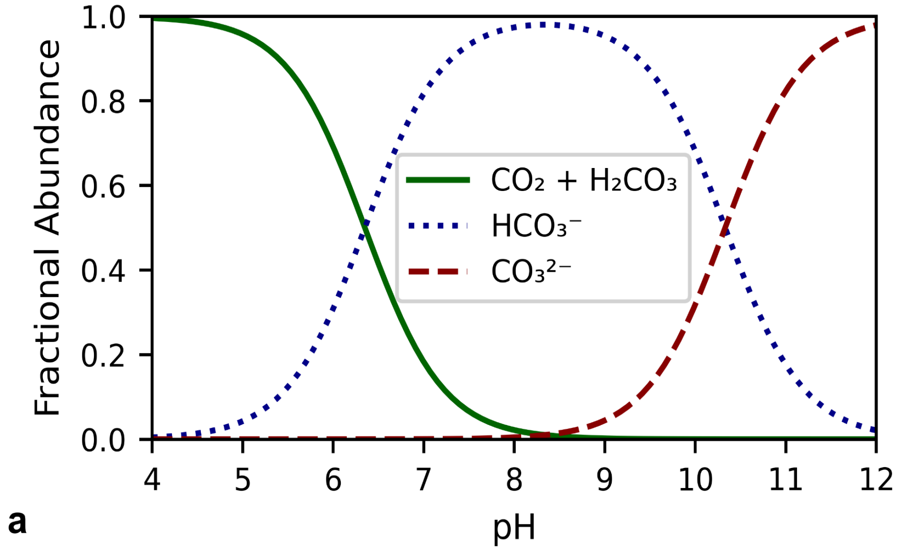

Figure 1.2. The carbonate system and its relationship to pH and alkalinity. **a**: Relative abundance of the carbonate system components across the relevant pH range under standard conditions (Stumm & Morgan, 1996).

1.4. Operational principles

Enhanced weathering

In the context of engineered CO_2 removal, accelerating (or *enhancing*) Earth's natural weathering processes has been proposed for over three decades (Lackner et al., 1995; Seifritz, 1990), and ERW shows significant potential for large-scale CO_2 removal (Beerling et al., 2020, 2025; Goll et al., 2021; Hartmann et al., 2009). Note that while ERW can also be carried out in coastal and aquatic environments (Renforth & Henderson, 2017), this methodology only considers the application of weathering material in terrestrial (land-based) environments, more specifically in soil.[3]

In essence, ERW involves three key components to speed up the natural weathering process (Abdalqadir et al., 2024; Andrews & Taylor, 2019; Clarkson et al., 2024):

1. **Suitable material selection**: Materials containing significant amounts of minerals with high weathering reactivity and appropriate cation content (especially Ca and Mg, but also Na and K) are preferred. These include, among others, mafic and ultramafic rocks that contain the minerals olivine, plagioclase and pyroxene, and metamorphic rocks that contain wollastonite, which not only react efficiently with CO_2 but may also improve soil fertility[4] (Haque, Chiang, et al., 2019). Other suitable materials include rocks containing silicate minerals that release alkalis and alkaline earth cations when they weather, as well as alkaline industrial wastes, particularly those containing fast-dissolving, cation-rich minerals (Khudhur et al., 2022; Renforth, 2019). Synthetic minerals for CDR are being explored as well (Chen & Kanan, 2025). The feedstock mineralogy and the cations and anions produced during dissolution significantly affect the amount of CO_2 sequestered (see Suitable feedstocks for ERW and table 1.2).
2. **Grinding**: Rock crushing and milling increase the reactive surface area by reducing mineral grain size and introducing surface defects (Fischer et al., 2012; Pedrosa et al., 2019), thereby accelerating dissolution rates and enhancing CO_2 uptake. The ideal grain size for ERW remains uncertain, although some studies suggest diminishing returns below certain particle sizes (Amann et al., 2022). In practice, optimal size also depends on non-chemical factors such as grinding costs, energy efficiency, and handling challenges or health risks associated with very fine dusts.
3. **Appropriate application settings**: Applying the weathering material to locations with optimal soil and climate conditions promotes the rate of weathering reactions. Such locations include e.g., sub-tropical regions with hot and humid climate, relatively low to moderate pH soils (pH ~5.2-7.2 (Bertagni & Porporato, 2022), and good hydrological drainage (Baek et al., 2023). Additionally, root exudates, fungal hyphae (Thorley et al., 2015; Verbruggen et al., 2021), invertebrates (Van Groenigen et al., 2019; Vicca et al., 2022), and soil microbial activity (Epihov et al., 2017; Perakis & Pett-Ridge, 2019) —including symbiotic Rhizobiaceae in leguminous crops— can enhance mineral dissolution (Haque, Santos, et al., 2019). Agricultural land is commonly targeted for ERW for several reasons, including suitable ambient conditions (presence of water and high CO_2 concentrations in the soil), and potential co-benefits to crop yields (see section 1.5). The routine disturbance of soils in croplands further facilitates mineral mixing and exposure to water.

---

[3] In the Puro Standard, weathering in controlled industrial conditions for the production of carbonated materials (also known as "accelerated carbonation") is covered by the Puro Standard methodology Carbonated Materials. Enhanced weathering in coastal areas and ocean alkalinization are currently (September 2025) not covered under the Puro Standard.

[4] The primary agronomic benefit of ERW applications is pH management, with a strong body of evidence linking reduced soil acidity to improved crop yields. Other potential benefits, such as nutrient contributions from mineral amendments, remain more speculative at present.

Suitable feedstocks for ERW

The most effective feedstock materials for ERW are those that combine high reactivity with high CO_2 sequestration potential. Optimal rock candidates contain silicate minerals characterized by low bond strength and enriched in divalent cations (Mg^{2+}, Ca^{2+}), each binding two moles of bicarbonate per mole of cation. Such minerals are predominantly found in ultramafic and mafic igneous rocks, but sedimentary rocks could also be of potential interest (Q. Zhang & Tutolo, 2022).

The maximum CO_2 removal capacity (CDR_{max}) of a rock sample can be calculated using an adapted **Steinour formula** (Lackner et al., 1995; Renforth, 2019) after sample digestion followed by XRF or ICP-OES analysis:

$$CDR_{max} = \frac{M_{CO_2}}{100} \times \left(2\frac{w_{CaO}}{M_{CaO}} - 1\frac{w_{CaCO3}}{M_{CaCO3}} + 2\frac{w_{MgO}}{M_{MgO}} + 1\frac{w_{K_2O}}{M_{K_2O}} + 1\frac{w_{Na_2O}}{M_{Na_2O}} \right) \quad (1.6)$$

Where, *M* is molecular weight (g/mol) and *w* is the oxide weight percentage. The $CaCO_3$ term of the equation corrects for calcium that is present in the form of carbonates, which implies a CDR potential of 1 mol CO_2 per mol $CaCO_3$ (eq. 1.4) rather than 2 mol CO_2 per mol CaO. This requires carbon content measurements in feedstock (see table 3.1). The equation above assumes complete carbonation of the oxides. This formula can also be used to estimate the sequestration potential of different minerals in their ideal form (table 1.2) but it is important to note that any ERW feedstock rock will be composed of multiple minerals.

Table 1.2. Examples of theoretical maximum potential for CO_2 removal by weathering of different minerals based on their ideal formula and oxide composition. Note that the ideal formula for minerals may differ significantly for any given mineral found in nature and the CDR_{max} values listed here only apply to the associated ideal formula and cannot straightforwardly form the basis for CDR_{max} calculations.

Group or subgroup	Name	Chemical formula (ideal)	CDR_{max} ($t_{CO2}/t_{mineral}$)
Olivine	Forsterite	$(Mg,Fe)_2SiO_4$	1.260
Pyroxenoid	Wollastonite	$CaSiO_3$	0.759
Clinopyroxene	Diopside	$CaMgSi_2O_6$	0.816
Orthopyroxene	Enstatite	$Mg_2Si_2O_6$	0.883
	Augite (Ca: (Mg,Fe) < 1)	$(Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)_2O_6$	0.692
Carbonate	Calcite	$CaCO_3$	0.440
Plagioclase feldspars	Anorthite (An)	$CaAl_2Si_2O_8$	0.310
	Albite (Ab)	$NaAlSi_3O_8$	0.176
	Labradorite	Intermediate composition between An and Ab (50-70% An)	0.259
	Andesine	Intermediate composition between An and Ab (30-50% An)	0.229
	Oligoclase	Intermediate composition between An and Ab (10-30% An)	0.199

Plagioclase feldspathoids	Nepheline	$Na_3KAl_4Si_4O_{16}$	**0.301**
	Leucite	$KAlSi_2O_6$	**0.202**
Mica	Glauconite	$(K,Na)(Fe_3+,Al,Mg)_2(Si,Al)_4O_{10}(OH)_2$	**0.150**

While CDR_{max} is useful to estimate the weathering potential of a given rock sample, it says little about the potential rate of weathering. The **Goldich dissolution series** (Goldich, 1938) ranks silicate minerals by stability during weathering. It is inversely related to Bowen's reaction series for igneous crystallization, which shows that minerals crystallizing at higher temperatures (e.g. olivine, calcium-rich pyroxenes, plagioclases) are less stable at Earth's surface and thus weather faster. This mineral-inherent susceptibility to weathering is then subject to environmental factors affecting the weathering rate, including temperature, pH, moisture, and CO_2 partial pressure.

1.5. Positive and negative aspects of ERW

ERW has strong potential for large-scale CO_2 removal due to the global abundance of suitable rocks, compatibility with existing agricultural practices, and possible co-benefits for soil and plant health (Healey et al., 2024; Swoboda et al., 2022). Its implementation typically does not require land use change (Beerling et al., 2020) and can even make use of industrial by-products such as cement kiln dust or recycled concrete (Khudhur et al., 2022; McDermott et al., 2024). When applied to croplands, ERW may improve soil pH, water retention, plant nutrient availability and regional air quality (Beerling et al., 2025), increase plant resistance to stress (Swoboda et al., 2022) while reducing fertilizer dependence and mitigating acidification in surrounding water bodies (Haque, Chiang, et al., 2019; Hartmann et al., 2013).

Despite its benefits, ERW remains a carbon removal technology with limited large-scale validation. While certain aspects of ERW such as deployment of rock dust and analysis of soil samples in agricultural settings are common practice and technologically advanced, monitoring weathering rates and carbon removal under field conditions remains technically challenging due to spatial and temporal variability and complex environmental dynamics (Mills et al., 2024; Power et al., 2025).

One key problem with ERW is that weathering in soils occurs gradually, often over years or even decades (Kanzaki et al., 2025), and is highly dependent on local conditions such as moisture and temperature—factors which may become more variable under climate change (Baek et al., 2023). Nevertheless, scientific field trials, as well as the development of measurement and modeling techniques have gained momentum in recent years (Cipolla et al., 2022; Dietzen & Rosing, 2023; Hasemer et al., 2024; Kanzaki, Chiaravalloti, et al., 2024; Milliken et al., 2025; Reershemius et al., 2023b; Suhrhoff et al., 2024; Te Pas et al., 2025).

Enhanced rock weathering is also associated with several practical and environmental risks that must be properly addressed. For example, fine grinding of rocks improves reactivity but the generated dust can pose respiratory hazards, creating a critical trade-off between CDR efficiency and human safety. Some rock types may also release potentially toxic elements like nickel or chromium during dissolution, and the fate of these elements under different risk exposure pathways is not well characterized for the specific conditions of ERW. Certain feedstocks may further contain other hazardous materials such as asbestiform minerals, or naturally occurring radioactive materials

(NORMs), posing additional health and environmental risks that require careful assessment and management. Besides the chemical constituents of the feedstock materials, other risks to soil health include e.g. the risk of soil compaction due to high application rates (versus lime or fertilizer inputs) during narrow seasonal application.

From the point of view of carbon removal, certain feedstock/soil/climate combinations (e.g. coarse material with low cation content in dry, cold, or alkaline environments) pose the risk of emitting CO_2 in the upstream process of deployment without providing CO_2 removal (F. L. Buckingham et al., 2022). Mining, grinding, and transport are also energy-intensive practices and may produce significant emissions, especially if fossil fuels are used, potentially compromising the net carbon benefit (Strefler et al., 2018).

Table 1.1. Positive and negative aspects of Enhanced Rock Weathering

Advantages	Limitations
High permanence	Monitoring and modeling challenges due to spatial and temporal variability
Abundant resources: Suitable rocks and application surfaces are widely available.	Air pollution risks from respirable dust during grinding and spreading
Established rock processing and spreading technology	High energy use and emissions from mining, grinding, and transport
Agricultural co-benefits (improved soil health, nutrient supply, pH, water retention)	Potential toxicity from harmful elements released during dissolution
No land use change required	Slow weathering kinetics and dependency on moisture, temperature, and mineralogy
Waste utilization (use of industrial by-products)	

1.6. Loss pathways associated with Enhanced Rock Weathering

Loss pathways are chemical or biological processes that can reverse the carbon removal achieved through ERW by converting previously sequestered carbon back into CO_2. Accounting for these losses is essential, especially in cases where the chosen C_{stored} quantification approach (see section 11.2) does not implicitly include them. Failing to do so may result in overestimating CDR due to the inclusion of false positives in the measured signal.

Non-carbonic acid weathering

ERW CDR is based on the hydrolysis and dissolution of weathering materials by protons derived from carbonic acid originating from dissolved atmospheric or soil-respired CO_2. This occurs in chemical competition with similar reactions driven by stronger, non-carbonic acids present in the soil environment, generated from biogeochemical and anthropogenic processes, including:

- Nitric acid (HNO_3) from nitrification or fertilizer inputs.
- Sulfuric acid (H_2SO_4) from sulfide oxidation or acid rain.
- Organic acids from microbial metabolism or root exudates.

These acids can also weather feedstock by release of base cations but without sequestering CO_2 in the process. Under certain measurement schemes, this can create a false weathering signal that must be corrected for rather than interpreted as CDR.

Secondary carbonate mineral formation

As detailed in section 1.3, secondary (pedogenic) carbonate formation can both sequester and release CO_2. This is because this process results in 1 mole of stable carbonate mineral but also 1 mole of CO_2 per 2 moles of bicarbonate (eq. 1.5). Thus, the CO_2 portion created by this reaction may require correction under some sampling schemes that do not cover the entire vertical extent of the NFZ.

Cation adsorption onto soil particles

The export of cations that were weathered from mineral feedstock in the NFZ can be decreased (temporarily) by cation adsorption onto the surface of soil particles, especially clays, organic matter, or oxides. Such cation adsorption can lead to alkalinity decrease and/or acidity increase in the soil porewater or be neutral in both regards, depending on whether the adsorbing cation replaces a cation of same or different valence or a proton. Acidity increase may imply CO_2 evasion and non-carbonic acid weathering. The adsorption of cations onto soil particles is generally reversible but models suggest that the magnitude is larger in soils with low base cation saturation and high cation exchange capacity (Kanzaki et al., 2025). Due to its reversibility, cation adsorption may be more accurately categorized as a “lag term” for ERW but this document categorizes it as a “loss term” for practical purposes because adsorbed cations represent a loss of alkalinity at any given point in time (e.g., end of monitoring period). Cation adsorption can be quantified using mild extraction methods targeting exchangeable cations.

Secondary silicate precipitation

The formation of secondary silicate minerals (especially clays) can support the disequilibrium in the soil solution that drives the weathering of feedstock. However, secondary silicate minerals can also limit feedstock dissolution by shielding the feedstock from the carbonic-acid weathering agent as well as by removing base cations (alkalinity) via sorption, co-precipitation and as part of the of the secondary mineral.

There is currently no reliable, commercially viable way to directly quantify low levels of secondary silicate formation in soils, but quantification approaches for C_{stored} that measure the decrease of feedstock cations (CAT_{Ti}, CAT_{WM}) or pore-water based methods (section 11.2) implicitly account for these losses if samples integrate across the entire depth of the NFZ. However, an additional problem can be caused by the tendency of clay minerals formed in upper soil strata (i.e., within the NFZ) to accumulate lower in the soil column (i.e., potentially below the NFZ), implying that monitoring within the NFZ is not enough to account for losses from secondary silicate formation. Pore-water measurements below the NFZ, e.g., via deep lysimeters, may currently be the only viable option to assess losses from secondary silicates by estimating the saturation index of such minerals (Mills et al., 2024).

Cation uptake by plants

Plant uptake of base cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) represents a key loss pathway of alkalinity that competes directly with carbon dioxide removal. When biomass is harvested, the base cations taken up by plants are effectively exported from the near-field weathering zone (NFZ), preventing them from contributing to long-term CDR via bicarbonate or carbonate formation. Accurately accounting for this cation flux is therefore essential for determining net CDR in ERW systems. For measurement schemes that do not inherently account for this loss term, this can be done by quantifying cation content in plant biomass and evaluating excess cation uptake in application sites compared to control sites.

Downstream carbon loss in rivers and the ocean

The ocean is the final storage site for CO_2 captured by ERW as bicarbonate or carbonate. However, some of this carbon can be lost during transport through rivers and lakes, or after entering the ocean, primarily via two mechanisms: 1) **carbonate mineral precipitation** and 2) **carbonate system equilibration**. The extent of these losses depends on local water chemistry.

Carbonate mineral precipitation can result in a 50% loss of previously captured CO_2 (eq. 1.5). This occurs when the saturation index of calcite ($SI_{calcite}$) exceeds a threshold:

$$SI_{calcite} = log_{10}([Ca^{2+}]_a \ * \ [CO_3^{\ 2-}]_a) / \ K_{sp} \tag{1.7}$$

Where $[Ca^{2+}]_a$ and $[CO_3^{2-}]_a$ are the calcium and carbonate ion activities, respectively, and K_{sp} is the solubility constant of calcite. $SI_{calcite}$ increases with higher temperature, higher concentrations of carbonate and calcium, and higher pH. While precipitation theoretically begins at $SI_{calcite} > 0.0$, in practice it typically occurs at $SI_{calcite} > 1.0$, which is uncommon in most rivers (Harrington et al., 2023; S. Zhang et al., 2025).

Carbonate system equilibration refers to shifts in dissolved inorganic carbon (DIC) speciation due to changes in temperature, salinity, and especially pH (see figure 1.2). In freshwater systems, lower pH can cause degassing of CO_2, while downstream increases in pH may reverse this and promote re-sequestration. In the ocean, high pH and salinity favor carbonate ions over bicarbonate, slightly reducing CO_2 uptake efficiency. This is because one mole of Ca^{2+} or Mg^{2+} can balance two moles of HCO_3^- but only one mole of CO_3^{2-}. Renforth & Henderson (2017) provide an equation to estimate the efficiency of carbon binding (C, mol) per mole-equivalent of alkalinity (A) as a function of pCO_2 (µatm), temperature (T, °C), and salinity (S, %):

$$\Delta C/\Delta A \ = (S{\times}10^{-3.009} + 10^{-1.519})\, ln(pCO_2) - (S{\times}10^{-2.100}) - (T{\times}pCO_2)(S{\times}10^{-7.501}) - (10^{-5.598}) - (T{\times}10^{-2.337}) + 10^{-0.102} \tag{1.8}$$

It is relevant to note that the ocean carbonate system is more complex than suggested by this equation, as vertical and horizontal mixing and advection impact gas exchange between water parcels and the atmosphere (Zhou et al., 2025). Consequently the retention of DIC in the ocean may be far greater than predicted under this (Kanzaki et al., 2023). As CO_2 is more soluble in colder water and bicarbonate dominates at lower salinity, ERW is more effective in cooler, fresher high-latitude oceans (Bertagni & Porporato, 2022).

Loss of excess carbon from rivers downstream of ERW application sites has been assessed using models (Harrington et al., 2023; S. Zhang et al., 2025). Zhang et al. (2025) assumed that 10% of weathering products from a 10 t ha^{-1} yr^{-1} application rate enter rivers, estimating ≤5% loss from degassing and precipitation. In contrast, Harrington et al. modeled scenarios with 100% of weathering products entering rivers at 10–50 t ha^{-1} yr^{-1}, thus representing a high-end case. Surface water chemistry (DIC and organic matter concentration, pH) in the local watershed affects the risk of this loss factor and special care needs to be taken in quantifying it for projects situated in more sensitive catchments.

In the ocean, abiotic carbonate mineral formation is inhibited by the chemistry of seawater. Instead, most marine carbonates are formed by shell-forming algae and the majority of these biotic carbonates re-dissolve into seawater (Renforth & Henderson, 2017). However, more research is needed to ensure that marine carbonate formation is indeed a negligible loss term for ERW and not significantly enhanced above baseline levels by additional alkalinity. While earlier modeling studies reported larger estimates for the total ocean loss term (carbonate system equilibration + carbonate mineral formation), a more detailed recent study estimated approximately 9% ocean loss for ERW with silicate mineral feedstock and 19% ocean loss for ERW with carbonate mineral feedstock (Kanzaki et al., 2023).

Table 1.3: Summary of loss pathways in ERW

Loss Pathway	Mechanism	Impact on CO_2 Removal	Quantification Considerations
Non-Carbonic Acid Weathering	Mineral dissolution by strong acids (e.g., HNO_3, H_2SO_4, organic acids)	Consumes feedstock without CO_2 uptake, warranting correction of false CDR signal under some circumstances	Quantification by soil-carbonate system modeling or soil anion flux measurements and estimations
Secondary Carbonate Formation	Precipitation of pedogenic carbonates from bicarbonate	Releases 1 mol CO_2 per 2 mol HCO_3^-; partial reversal of silicate-feedstock based ERW	Quantification by SIC measurements if monitoring does not cover full NFZ depth
Cation Adsorption	Base cations adsorb to soil particles after weathering	Delays alkalinity export; may release protons and promote CO_2 evasion	Quantified via exchangeable cation extraction; varies with soil CEC and saturation
Secondary Silicate Precipitation	Formation of clays or other silicates incorporating base cations	Reverses weathering and inhibits vertical export of alkalinity	No feasible quantification method but many C_{stored} quantification schemes inherently correct for it in NFZ; may also occur below NFZ
Plant Cation Uptake	Plants absorb base cations and release protons	Reverses bicarbonate formation; exported cations reduce long-term CDR	Quantifiable by plant biomass cation content compared between application and control sites.
Riverine Carbon Loss	CO_2 degassing or carbonate precipitation in rivers and lakes	Up to 5% loss under many conditions; higher in high-input cases	Assessed and potentially modeled based on river chemistry data
Oceanic Carbon Loss	Carbonate system equilibration and biogenic carbonate formation	Estimated loss of ~9% (silicates) or ~19% (carbonates)	Modeled using ocean chemistry data; biogenic carbonate formation needs further study

1.7. Counterfactuals

In the context of this methodology, counterfactuals refer to what would have happened to CO_2 fluxes and environmental processes in the absence of the ERW intervention. Establishing accurate counterfactual scenarios is essential to quantify the net carbon removal attributable to ERW, by comparing observed outcomes against realistic baseline conditions without ERW deployment (see section 6.2 and section 11.1).

Agricultural liming

Applying ground limestone (a rock type containing mostly calcium carbonate) to fields is a common agricultural practice worldwide. It has the purpose of raising soil pH, which can result in a variety of benefits (e.g., decreased metal toxicity, increased nutrient availability). Despite the prevalence of liming, it is not necessarily true that liming should be considered as the counterfactual baseline, because liming can be prohibitively expensive in some farming systems, locales, and years.

From a carbon accounting perspective, agricultural liming has been categorized as a net carbon source to the atmosphere by the IPCC[5], because the fossil carbon in limestone is a stable form that is brought into a reactive form and setting. At low soil pH, the limestone can be dissolved via reaction with non-carbonic acids, which would release the carbonate from the limestone as CO_2. However, if dissolution occurs via carbonic acid weathering, the reaction depicted in eq. 1.4 applies, resulting in the sequestration of 1 mol of CO_2 per mol of calcium carbonate dissolved. Thus, the carbon budget implications of agricultural liming are highly context-specific (Hamilton et al., 2007).

Reduced fertilizer application

ERW interventions can improve soil pH, nutrient availability, and cation exchange capacity, potentially reducing the need for synthetic fertilizer inputs. Such reductions could, in principle, lead to lower upstream CO_2 emissions from fertilizer production and decreased N_2O emissions from fertilizer use.

However, the current consensus is that reductions in non-CO_2 greenhouse gas emissions, such as N_2O or CH_4, should not be included in the net CDR calculation of ERW projects (Mills et al., 2024). While these emission reductions are important for understanding the overall greenhouse gas balance and should be quantified and tracked as part of holistic environmental accounting, they are not considered part of the CO_2 removal to be credited within the scope of this methodology.

Counterfactual feedstock weathering

Another relevant counterfactual is the natural weathering of the feedstock material under the scenario in which it was not used for ERW. For example, had the feedstock material not been used for ERW but weathered in its original quarry, waste pile, or natural outcrop, some CO_2 removal by weathering may have occurred anyway.

---

[5] 2006 IPCC Guidelines for National Greenhouse Gas Inventories, and 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

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 Enhanced Rock Weathering 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 weathering material deployment system.
- The owner of the weathering material 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 weathering material).

2.1.2. The CO_2 Removal Supplier shall be 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 activity, as well as monitoring and quantifying the net carbon removal. To this extent, the CO_2 Removal Supplier shall establish clear responsibilities and liabilities with its supply-chain partners, external operators, or any other involved party, to enable collection of the necessary data for verification.

2.1.3. The CO_2 Removal Supplier shall retain the sole right to claim CORCs from the Enhanced Rock Weathering activity, and contractually agree with any supply chain partners, external operators, or any other involved party that they have no such right. For further details on prevention of double counting, see section 3.5.

2.2. Production Facility

The Production Facility is defined as the ensemble of physical assets necessary to perform the end-to-end activities associated with an Enhanced Rock Weathering activity, and subject to the Production Facility Audit as per the terminology defined in the Puro Standard General Rules.[6]

2.2.1. For the purposes of this methodology, a Production Facility comprises the following components within the activity boundary (see figure 7.1):

a. one or several weathering material sourcing sites;
b. potential additional processing sites or other infrastructure for weathering material processing (such as grinding or comminution);
c. a logistics chain for weathering material transportation;

---

[6] Available in the Puro Standard document library.

d. one or several weathering material application sites;
e. one or several control sites (see section 11.1); and
f. the weathering material itself.

2.2.2. All industrial facilities (i.e. weathering material sourcing and processing sites) under the same Production Facility shall be operational at the time of the Production Facility Audit.

2.2.3. The CO_2 Removal Supplier may update the Production Facility definition without having to undergo a new Facility Audit provided that such changes are in compliance with the requirements set in this methodology and the Puro Standard, approved by the Issuing Body, and verified during an Output Audit.

2.2.4. Any change in the definition (i.e., components, borders, feedstock sourcing, etc.) 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 2.2.1). These updates shall require validation by the auditor during the subsequent Production Facility Audit or Output Audit.

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

a. The Production Facility Auditor verifies the conformity of the Production Facility against the requirements of this methodology and other Puro Standard requirements, as well as the proofs and evidence needed from the CO_2 Removal Supplier.

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

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

   ii. documentation evidencing that the CO_2 Removal Supplier has registered the Production Facility in the Puro Registry;

   iii. locations of the weathering material sourcing sites and weathering material application sites and control sites included in the Production Facility;

   iv. whether the Production Facility has benefited from public financial support; and

   v. date on which the Production Facility becomes eligible to issue CORCs.

2.2.6. The Crediting Period in this methodology is 10 years starting from the first date of the first Monitoring Period.[7]

a. The Crediting Period may be renewed twice by successfully undergoing a new Production Facility Audit.

b. The Crediting Period shall not overlap with another Crediting Period for the same Production Facility.

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 during the ERW activity when the deployed weathering material has 1) chemically reacted to sequester CO_2, and 2), the weathering proxy (cation or bicarbonate) has either leached out vertically to below the NFZ (for quantification approaches A1-A5, see section 11.2) or formed secondary carbonate minerals (quantification approach A6), and 3) the data records thereof can be verified.

2.3.2. The amount of CORCs issued at a given time shall be based on the amount of CO_2 sequestration that *has already occurred* by the time of the Output Audit (i.e., crediting occurs *ex post*).[8]

2.3.3. The CO_2 Removal resulting from Enhanced Rock Weathering activities certified under this methodology is considered to be permanent for at least 1000 years.

---

[7] In accordance with the Puro Standard General Rules, the Crediting Period is defined as the period in which verified CO_2 removal Output attributable to a certified Production Facility can result in the issuance of CO_2 Removal Certificates (CORCs), and the Monitoring Period is defined as the the time between the first date and last date of the Output Report. For further details and requirements on these periods and the certification process in general, see also the Puro Standard General rules section 2: Certification Process Description (available in the Puro Standard document library).

[8] The CORCs associated with a given ERW activity are issued gradually over the lifetime of the project, as the deployed weathering material reacts over time to sequester CO_2. In practice, the speed of the weathering reactions can vary depending on factors such as weathering material composition and soil properties, and it can take several years or even decades for all the deployed weathering material to fully react.

3. Eligibility requirements

3.1. Overall principles

An eligible activity is capable of permanently sequestering CO_2 of atmospheric or biogenic origin through chemical weathering of mineral feedstocks by safely and durably converting and storing CO_2 as dissolved (bi)carbonate ions or as solid mineral carbonates. In practice, the CO_2 Removal activity consists of spreading weathering materials onto soil (see figure 3.1).

It is important that the requirements for Enhanced Rock Weathering activities ensure durable, robustly quantifiable CO_2 Removal that leads to no net harm[9] to the environment (e.g. contamination by heavy metals), or to society (through e.g. loss of arable land, exposure to hazardous materials or dust, or other health risks).

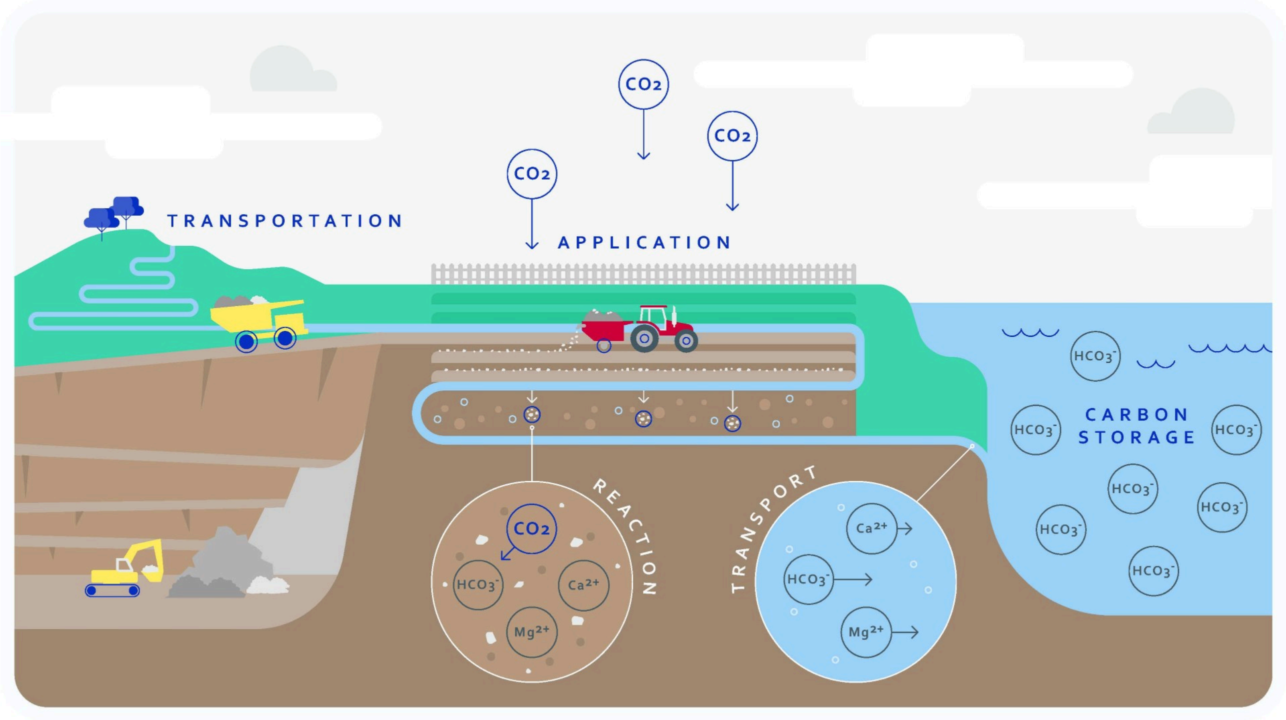

Figure 3.1. A schematic depiction of a CO_2 removal activity within the scope of this methodology.

3.2. General eligibility

3.2.1. An eligible activity involves sourcing eligible feedstock (see section 3.6) and applying it to the soil of eligible application sites (see section 3.9) under conditions that promote CO_2 sequestration as weathering products (primarily in the form of carbonate and bicarbonate aqueous ions), or as reprecipitation of weathering products (primarily as calcium carbonate solids).

---

[9] While the ERW activity has significant potential to help mitigate the global effects of climate change, it is paramount that the weathering material sourcing, handling, and spreading activities are conducted in a manner such that the benefits overwhelmingly outweigh the disadvantages.

3.2.2. The CO_2 Removal Supplier shall obtain all permits and/or local legal authorizations required to conduct weathering material application activities before the start of application. The CO_2 Removal Supplier must also provide proof of having the rights necessary to enable appropriate monitoring at any stage within the activity boundary and monitoring period during the lifetime of the Production Facility.

3.2.3. All installations and operations relating to the Enhanced Rock Weathering activity shall comply with all applicable laws, regulations and other statutory requirements, including but not limited to environmental regulations, and regulations for weathering material processing and handling.

3.2.4. All infrastructure and equipment used for weathering material sourcing, processing, transport, and application shall be constructed or installed according to national best practices and in compliance with statutory requirements. All infrastructure shall be approved by local authorities and hold relevant permits for operation. Examples of such installations and equipment include weathering material warehouses and processing facilities (e.g. for screening and grinding).

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

3.2.6. The CO_2 Removal Supplier shall demonstrate the baseline carbon removal scenario for their intended Enhanced Rock Weathering approach. The baseline is a conservative scenario of what likely would have happened to the sourced material(s) and the application site(s) without the Enhanced Rock Weathering activity. Further requirements on the baseline determination are found in section 6.2.

3.3. The CO_2 Removal Supplier

The activities associated with a particular Enhanced Rock Weathering activity can involve multiple site operators collaborating within the project boundary. While the CO_2 Removal Supplier can act as the weathering material 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 must clearly establish and demonstrate ownership of the CO_2 removal activity, either by providing proof of direct ownership or, where applicable, through contractual agreements with external operators.

a. The CO_2 Removal Supplier shall prove with contracts or authorization documents its sole ownership of the durably stored carbon.

b. An external operator refers to any party—such as a logistics provider or the operator of the weathering material sourcing or deployment system—who acts on behalf of and under the direction of the CO_2 Removal Supplier to deliver services related to the Enhanced Rock Weathering activity.

3.3.3. When any part of the Enhanced Rock Weathering 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—to the applicable extent—at least address:

- Conducting the required monitoring activities such as sampling, set-up of measurement tools, maintenance, and the monitoring of individual parameters.
- Preventive and corrective measures taken in case of a reversal event (see section 4.3).
- Post-deployment and site closure requirements.

3.3.4. When any part of the Enhanced Rock Weathering activity is contracted to an external operator, the CO_2 Removal Supplier shall provide the contractual information necessary for assessing compliance with this methodology, the Puro Standard General Rules and other Standard Requirements,[10] as well as any applicable local laws, regulations, and 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 weathering material deployment operator, documentation establishing that the weathering material received by the deployment operator will be deployed into eligible application sites.
- Proof of sole ownership to the weathering material sourced, transported or deployed, 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.
- Documentation that the environment, health and safety plan (rule 4.4.5) is applied also to the external operator.

3.3.5. The CO_2 Removal Supplier is responsible for ensuring that sufficient data is available and accessible for auditing and verification that the Enhanced Rock Weathering activity is compliant with the requirements of this methodology and other applicable Puro Standard

---

[10] Available in the Puro Standard document library.

Requirements[11]. This includes but is not limited to delivering the necessary data to assess the eligibility of the activities, and quantify the 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 13).

3.4. Additionality

One of the key requirements in the Puro Standard is to ensure that the credited CO_2 Removal is additional, meaning that it would not have occurred in the absence of the incentive provided by carbon credits. Additionality assessment is essential for the integrity and credibility of the carbon crediting program, as it ensures that the credits represent real and additional CO_2 Removal that contributes to mitigating climate change. Additionality is comprised of three different aspects:

- **Regulatory additionality**: the project is not required by existing laws, regulations, or other binding obligations.
- **Baseline/carbon additionality**: the activity results in higher volumes of carbon removals than the likely baseline alternatives.
- **Financial additionality**: the CO_2 removals are a result of the incentive provided by carbon credits.

3.4.1. The CO_2 Removal supplier shall demonstrate additionality in accordance with the Puro Additionality Assessment Requirements.[12] This entails demonstrating that the Enhanced Rock Weathering activity is not required by existing laws, regulations, or other binding obligations, that the CO_2 removals are a result of carbon finance, and that the removal activity is carbon net-negative.

3.5. Prevention of double-counting

The purpose of preventing double counting is to exclude the possibility of more than one CORC being issued for the same volume of CO_2 Removal, and that an issued CORC represents the sole proof of ownership of the CORC itself, as well as the associated CORC Attributes.

3.5.1. The CO_2 Removal Supplier shall demonstrate prevention of double counting in accordance with the requirements in the Puro Standard General Rules.[13]

---

[11] Available in the Puro Standard document library.

[12] Available in the Puro Standard document library.

[13] Available in the Puro Standard document library. In the current version of the Puro Standard General Rules (version 4.2), the relevant requirements are found in section 3.5 PREVENTING DOUBLE COUNTING.

3.6. Feedstock eligibility and characterization

3.6.1. An eligible weathering material shall consist primarily of natural minerals and rocks, or other similar substances (e.g. alkaline waste materials such as slags, mine tailings, recycled concrete, or cement kiln dust) capable of undergoing carbonic-acid weathering to sequester CO_2 as (bi)carbonate ions or solid carbonate minerals.

a. The weathering material may further contain incidental associated substances from the sourcing or processing of materials (e.g. clays or other non-weathering materials, or innocuous impurities), as well as tracers or other substances added to assist in the monitoring and verifying of the CO_2 sequestration process.

b. The overall chemical composition of the weathering material (i.e. including the weathering material as well as any impurities and other substances) shall comply with all applicable local laws, regulations, and other statutory requirements, as well as all requirements imposed by relevant external operators or contract partners (e.g. logistics operators or land owners, see section 3.3).

3.6.2. The CO_2 Removal Supplier shall undertake physical, chemical and mineralogical analyses of the weathering material in order to provide evidence that the concentrations of potentially toxic elements (PTEs) in the feedstock do not exceed the limits defined in the applicable local, regional, national or international legislation (table 4.3, rules 4.5.2 and 4.5.3).

a. The geochemical assay shall be conducted at least once annually or after every 5000 tonnes of weathering material applied, whichever comes first. Additionally, the testing shall be conducted whenever *at least one* of the following conditions is fulfilled:

   i. Weathering material is spread to the field site of a new Production Facility (i.e. beginning of project).

   ii. Weathering material is sourced from a new sourcing site (e.g. a new quarry or supplier).

b. The analysis shall cover at least the measurements listed in table 3.1.

c. The analyses shall be performed for a statistically representative sample of the entire deployed feedstock in the following ways:

   - The measurements shall be conducted by using appropriate, peer-reviewed scientific best practices or appropriate standard methods (examples referenced in table 3.1). Appropriate, certified reference material shall be used for calibration and available for reporting to the Issuing Body.
   - The measurements shall be conducted in laboratories that must be accredited by national authorities and comply with international testing standards (e.g. ASTM, ISO, AS, D).

- When using internal laboratories (conducted by the CO_2 Removal supplier), detailed protocols shall be shared with the Issuing Body for validation.

d. The analyses shall be used to properly identify and name the feedstock rock based on international protocols approved by the International Union of Geological Sciences (Maitre et al., 2005).

Table 3.1. Overview of required measurements for feedstock characterization.

Measurement	Analytical method with reference	Requirement
Moisture content	Measured shortly before application to field (e.g., ISO 11465:1993)	Required
Specific surface area	Gas adsorption method (ISO 9277:2022)	Recommended (where particle size distribution alone does not sufficiently inform potential reaction kinetics)
Particle size distribution	Sieving (ISO 9276-1:1998, lower precision) or laser diffraction (ISO 13320:2020, higher precision)	Required
Major element oxide composition (at least: CaO, MgO, K_2O, Na_2O, P_2O_5, SO_4, SiO_2, Al_2O_3, Fe_2O_3, MnO/Mn_3O_4, TiO_4)	XRF (Oyedotun (2018)/ISO 12677:2011), ICP-MS (ISO 17294-1:2024) or ICP-OES (ISO 11885:2007) or AAS (ISO 26845:2008) after acid digestion (EPA 3050B)	Required
Heavy metal content (listed in table 4.3)	XRF (Oyedotun (2018)/ISO 12677:2011), ICP-MS (ISO 17294-1:2024) or ICP-OES (ISO 11885:2007) or AAS (ISO 26845:2008) after acid digestion (EPA 3050B)	Required
Carbon content	Dry combustion (ISO 10694:1995)	Required
Loss on ignition	Weight loss from loss of carbonates, water (from hydrated minerals or clays), and organics upon heating a pre-weighed sample to 900-1000 °C	Recommended (to assess weathering potential)
Quantitative mineral composition (relative amounts)	X-ray diffraction (XRD) coupled with e.g. Rietveld refinement (Ali et al., 2022)	Required
Asbestos	Polarized Light Microscopy (PLM, ISO 22262-1:2012) or Transmission Electron Microscopy (TEM, ISO 13794:2019) or Scanning Electron Microscopy (SEM, ISO 14966:2019)	Required if feedstock consists of serpentine minerals (chrysotile) or amphibole minerals (e.g., tremolite, actinolite)
Radionuclides	Gamma spectroscopy (ISO 18589-3:2023) or ICP-MS (ISO 17294-2:2023)	Required if feedstock consists of phosphate rocks, granite, pegmatites, tectonically altered or volcanic rocks, mine tailings or industrial byproducts

3.7. Feedstock processing and deployment

3.7.1. The CO_2 Removal Supplier may, where necessary, process the sourced weathering material prior to deployment to enhance the weathering rate of the material, or to render it otherwise more suitable for the ERW activity. For example, such processing can include additional grinding, mixing with other sourced feedstocks, and other similar processing steps.

3.7.2. The CO_2 Removal Supplier shall evidence that within each field, the weathering material is deployed evenly in accordance with the targeted feedstock application density (tonnes of weathering material deployed per hectare), and utilizing suitable equipment (such as a spreader).

3.7.3. The CO_2 Removal Supplier shall keep records of weathering-material deployment, which shall include at least the following information:

a. The exact dates and times of each weathering material deployment to the application site.

b. Precise geographic records (GPS coordinates, GIS mapping) of all weathering material application sites used in the project. Each deployment event shall be linked to its specific location within the field site to enable accurate monitoring and verification of carbon storage over time. The accuracy of geographic mapping should be sufficient to inform monitoring and sampling efforts.

c. The feedstock application density for each deployment with precise reference to time and location. Feedstock density estimates may be based on agricultural spreading logs or direct measurements of e.g., cation concentrations before and just after feedstock application in representative soil samples.

The exact location, boundary, and timeline records shall be securely archived and readily available as required for compliance, monitoring, reporting, and verification purposes. Any changes to the storage site locations, boundaries, or deployment schedules shall be documented and reported to the Issuing Body. The records shall be made available to the Auditor.

3.8. Feedstock sustainability and traceability of origin

3.8.1. The CO_2 Removal Supplier shall demonstrate and keep records (i.e. traceability, chain of custody) of the origin and type of the feedstock(s) used as weathering material, as further detailed in subrules a-c.

a. For each batch of feedstock, the origin and type records shall include at minimum:
    i. Unique identification number or equivalent identifying information;
    ii. Description of the material based on the geochemical characterizations specified in table 3.1;
    iii. Date of delivery and production;

   iv. Mass of material received;
   v. Name and location of the entity producing the material (e.g. quarry, industrial plant);
   vi. Geographic location of origin of the material.

b. If feedstock is sourced from multiple origins (e.g. different quarries), records shall be maintained separately for each source, and must indicate the proportion of the total material supplied from each source.

c. Any share of the weathering material for which origin or type records cannot be evidenced is not considered eligible, and thereby its share of CO_2e shall be excluded from the quantification of CORCs.

3.8.2. The CO_2 Removal Supplier shall evidence that all weathering materials are sourced from operations that comply with the following criteria:

a. The extraction, production, processing, handling, and transfer of the material shall comply with all applicable national and local laws and regulations, including those governing mining, waste management, industrial by-products, labor, occupational health and safety, and environmental protection.

b. For quarried or mined rock feedstocks, the supplying entity shall hold valid extraction permits and licenses, and shall operate in compliance with all environmental and safety regulations in the jurisdiction of origin.

c. For industrially derived feedstocks (e.g., slags, ashes, fines, mine tailings, or other alkaline industrial waste materials), the producing entity shall demonstrate legal authorization to generate, manage, and transfer the material, and the material shall not be classified as hazardous waste under applicable regulations.

d. Any material for which the supplier cannot provide verifiable documentation of legal origin, authorization, or non-hazardous classification shall be considered ineligible. If ineligible material is deployed in the application site, the corresponding share of CO_2e shall be calculated and excluded from the quantification of CORCs.

3.9. Field site eligibility and characterization

3.9.1. The weathering material shall only be applied to the soil at eligible land-based application sites (see rule 3.9.2). Weathering material shall not be applied to seas, lakes, rivers, and other bodies of water including their immediate vicinities such as shorelines, beaches and other similar coastal regions where the weathering material is or can reasonably be expected to be in constant or nearly constant direct contact with a body of water. However, the weathering material may be applied to irrigated land.

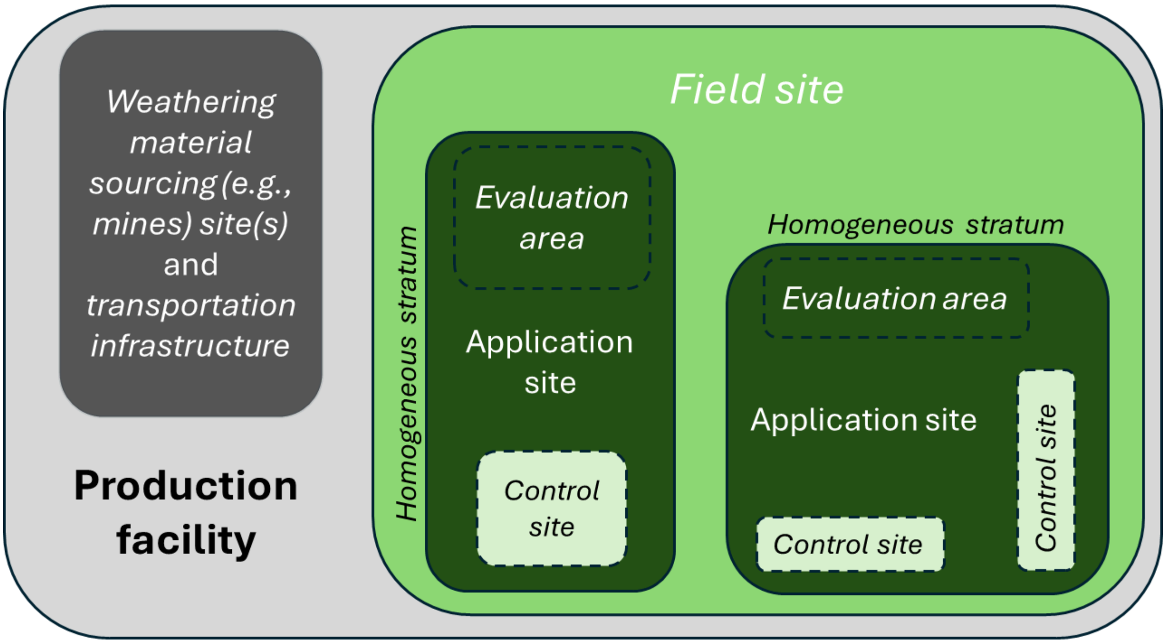

Figure 3.2. The Production Facility (light grey) and its subunits. A field site (medium green) contains homogeneous strata (defined after pre-application soil characterization), which contains control sites (light green; one or more) and an application site (dark green). Optionally, a more densely sampled evaluation area can be defined within the application site. Note that the field site may have parts that are dormant with respect to ERW during some or all portions of the crediting period and therefore not part of homogeneous strata.

3.9.2. An eligible **field site** shall consist of any number of plots of land with similar characteristics (rule 3.9.3) where weathering material is applied as part of the Enhanced Rock Weathering activity, as further defined in subrules a-c.

a. For the purposes of this methodology, a **plot of land** is defined as a contiguous piece of land (i.e. land that is either connected or separated only by a public or private roadway, waterway, easement, or other right of way) of predetermined area, boundaries, and geographic location.

b. An **application site** is a collection of geographically proximate plots that are similar in relevant parameters (see rule 11.1.1), that are grouped together for monitoring purposes, and to which weathering material is applied. An application site can consist of physically separated plots, and need not be contiguous. An **evaluation area** represents the areal subset of the application site area that needs to be monitored as further specified in rule 11.1.5.

c. A **control site** is a plot or collection of geographically proximate plots. These plots can be physically separated, so a control site need not be contiguous but it needs to have similar characteristics with regards to monitoring and agricultural management as the associated application site as defined in section 11.1, especially rule 11.1.1. Control sites represent the *business-as-usual* (or *baseline* or *counterfactual*) scenario and shall be monitored in order to serve as a baseline reference for quantification of Enhanced Rock Weathering in application sites.

3.9.3. All field sites registered under the same Production Facility shall have consistent:

- Geographic location (at least within a single country and within the same major catchment, i.e., not divided by a continental watershed).[14]
- Climatic conditions (should span at most three Köppen-Geiger climate zones (Beck et al., 2018)).

3.10. Positive sustainable development goal impacts

The Puro Standard General Rules and the associated SDG Assessment Requirements[15] contain the general requirements related to describing and evidencing positive impacts on Sustainable Development Goals (SDGs)[16] that apply to all methodologies. The Puro SDG Assessment Requirements includes a list of project-level indicators, SDG Attributes, for demonstration of positive impacts on SDGs. Additional SDG Attributes can be proposed by external actors via a procedure described in those requirements. Certification of SDG Attributes requires collection of project-specific data and third-party verifications. Certification of SDG Attributes is optional and comes with additional certification fees.

In the context of Enhanced Rock Weathering, positive SDG impacts might be related to targets[17] such as improved agricultural productivity (SDG target 2.4), action to combat climate change and its impacts (SDG target 13), increase in the buffer capacity of the ocean (SDG target 14.3), or restoring degraded land (SDG target 15.3).

3.10.1. If the CO_2 Removal Supplier decides to not apply for additional certification of SDG Attributes, the CO_2 Removal Supplier must nevertheless provide in the Project Description a qualitative description of expected positive impacts on SDGs in accordance to Puro's SDG Assessment Requirements[18]. This description shall be project-specific, based on the actual operations (e.g. type of feedstock used, measurements of crop productivity).

3.10.2. The CO_2 Removal Supplier may decide to pursue certification of SDG Attributes at any time throughout the crediting period. In that case, the CO_2 Removal Supplier shall provide the following documentation:

a. for the Facility Audit, prepare an SDG Report based on the template provided, in which the selected SDG Attributes are described. The SDG Report must include a plan of how the requirements for each selected SDG Attribute will be

---

[14] This is required to enable the determination of a unique and unambiguous Host Country for the removal activity.

[15] Available in the Puro Standard document library.

[16] 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.

[17] 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.

[18] Available in the Puro Standard document library.

demonstrated throughout the course of the crediting period. The plans described in the SDG Report must also be reflected in the Monitoring Plan (e.g. in an appendix specific for SDG Attributes).

b. for the Facility Audit, provide in the Project Description a description of expected positive impacts on SDGs based on the selected SDG Attributes and their associated monitoring plan, and any outcome already available.

c. for the Facility Audit or subsequent Output Audits, i.e. whenever available, provide the data required to demonstrate the achieved positive impact on SDGs. This information will be verified by the appointed auditor, and if successful, result in SDG Attributes associated for the applicable CORCs (see details in the SDG Assessment Requirements).

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 ERW activity. Several risks concerning climate, ecosystems, and human health 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, 2017). 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 activity 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[19]). 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 5.3.1).

An eligible ERW activity must also take into consideration multiple **environmental and social risks**, which may negatively impact 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 and in this section of the methodology, further requirements and guidelines are also found in the Puro Stakeholder Engagement Requirements, the Puro Stakeholder Engagement Report Template and the Puro Environmental and Social Safeguards Questionnaire[20].

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.

---

[19] Available in the Puro Standard document library.

[20] Ibid.

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, respectively).

For all types of risk associated with the ERW 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 ERW project 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 feedstock sources (see sections 3.6 and 3.8) or the application site (see section 3.9). 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 an ERW project.

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 environmental risk assessment (ERA) prior to project initiation, based on the following criteria:

a. The scope of the assessment shall cover all stages (feedstock sourcing, processing, transportation, deployment and monitoring) within the activity boundary (see rule 7.2.2).

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.

c. The assessment shall comply with the requirements of this methodology, the Puro Standard General Rules[21] and other Puro Standard Requirements[22], as well as any applicable local laws, regulations, and other binding obligations. If country-specific threshold values exist and are more stringent than other recommended values in this methodology, the country-specific values shall prevail.

d. The environmental risk assessment performed by the CO_2 Removal Supplier shall follow the guidance from the US EPA,[23] the EU EFSA,[24] or other locally relevant institutions. The environmental risk assessment shall contain the outline below (see details on the mitigation hierarchy framework above in section 4.2):

---

[21] Available in the Puro Standard document library.

[22] Ibid.

[23] About Risk Assessment | US EPA

[24] Environmental risk assessment | EFSA

- Step 1. Problem Formulation
- Step 2.1. Hazard characterisation
- Step 2.2. Exposure characterisation
- Step 3. Risk characterisation
- Step 4. Risk mitigation measures
- Step 5. Conclusions regarding the ERW activity

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 can include direct, indirect, or cumulative risks.
   - The impacts can 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.

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 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 analyses conducted by the CO_2 Removal Supplier (see section 11).
   - 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[25] and the Puro Stakeholder Engagement Requirements.[26]

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

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**

---

[25] Available in the Puro Standard document library.

[26] Ibid.

4.2.3. The risk assessment shall, to the extent possible, be based on the actual project data acquired during the ERW 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 effectiveness of any carbon removal activity depends on the ability to store carbon safely and durably. In this context, a reversal risk refers to any event or condition that may compromise the integrity of carbon storage, leading to the unintended re-emission of previously sequestered carbon back into the atmosphere.

It is important to distinguish reversal risks from carbon losses (see section 6.3), which result from re-emission pathways known or assumed a priori, and which therefore are accounted for at the time of CORC issuance. In contrast, **reversals** refer to previously unknown or unanticipated re-emissions that occur after the issuance of CORCs, and are addressed via the procedures described in the Puro Standard General Rules.[27] Reversal events may include physical disturbances or environmental changes, whether caused by natural phenomena or human activities, that affect temporarily or permanently the behavior of stored carbon.

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 Supplier to define measures to address those risks and compensate for any reversals. When all of the eligibility requirements (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 9.6.

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) and general risk assessment criteria detailed in section 4.2. The assessment shall include reversal risks arising from:

---

[27] Available in the Puro Standard document library.

a. Natural processes leading to the reacidification of soils or waters that could reverse carbonate or bicarbonate formation, such as acid rain or other acid accumulation

b. Anthropogenic interference, including but not limited to:

  - Land use changes that would lead to sequestered carbon reversals such as repeated applications of ammonium-based fertilizers
  - Acidic mine drainage or industrial spills that lead to soil acidification

4.4. Requirements for environmental and social risk assessment and management

The Puro Standard General Rules[28] 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 ERW 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 Rules[29], or any applicable local statutory requirements, in order to ensure that the ERW 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 ERW 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 ERW 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 ERW 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 ERW 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).

---

[28] Available in the Puro Standard document library.

[29] Ibid.

- Description of the ERW 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).
    - Local communities (e.g., due to noise, pollution, limiting access to recreationally significant areas).
    - Sites of cultural or archaeological significance (e.g. ancient burial sites).
- 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[30] 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[31] 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.[32] 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.[33]

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 and physical harms. The plan shall contain at least the following elements related to environmental risks and human health risks:

---

[30] Available in the Puro Standard document library.

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

[32] 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).

[33] Ibid., p. 5.

a. Identification and listing of any potentially harmful chemical compounds and potentially dangerous objects and procedures employed at any stage within the activity boundary.

b. Risk assessment and mitigation measures for chemical or physical injuries (for example, due to inhalation, ingestion, or skin contact with harmful substances, or accidents with machines) 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.

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

During the weathering reactions, elements are released into the soil. Depending on the material composition, elements released can also include potentially toxic elements (PTEs) which above certain levels may have detrimental effects to the environment and be harmful to living organisms, including plants, animals, and humans. PTEs relevant to this methodology include heavy metals (e.g., nickel, chromium VI, cadmium, uranium), radionuclides (e.g. ^{40}K, ^{226}Ra, or ^{232}Th), and other contaminants such as asbestos. These may have negative effects on ecosystems (toxic for fauna and flora, contamination of water resources) and humans (health effects via dust inhalation, direct exposure to contaminated soil, ingestion through the food chain or contaminated water).

Beyond PTEs, environmental risks associated with ERW may include undesirable changes to soil biogeochemistry. While ERW can improve soil pH, increase nutrient availability (e.g., Ca, Mg), and boost crop yields, overapplication or unsuitable rock types may disrupt soil chemistry, lower organic carbon levels, or introduce harmful trace metals, potentially affecting plant health and productivity.

This section outlines the key risks 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
Soil organic carbon (SOC)	Soil organic carbon may decrease as a consequence of ERW activity	Medium; monitor SOC concentration before feedstock application and at the end of monitoring periods	Use SOC concentration analysis values to ensure that SOC concentrations in soils do not decrease drastically
Heavy metals	Heavy metal concentrations in feedstocks and soils may lead to bioaccumulation, toxicity, and groundwater contamination	Low to medium; Evaluate metal concentrations in feedstocks and post-deployment soils	Use feedstock analysis values to ensure that metal concentration in feedstocks and soils are within regulatory requirements and beneath established safe thresholds
Asbestos	Naturally occurring fibrous minerals in some (ultra)mafic rocks can become airborne during grinding or application	High health hazard if present; inhalation may cause cancer; risk depends on feedstock geology and particle handling	Avoid asbestos-prone rocks; conduct mineralogical testing; control dust; enforce PPE and safe material handling protocols
Radionuclides	Naturally occurring radioactive elements (e.g. uranium, thorium) may be present in trace amounts in some rock types	Generally low; potential exposure via dust inhalation or leaching depends on rock source and application scale	Screen feedstocks for radioactivity; avoid high-U/Th rocks; conduct leach tests; monitor radon in enclosed facilities
Respiratory Risks	Inhalation of fine rock dust (e.g., PM10, respirable silica) during crushing, handling, or spreading can impair lung function	Medium to high; prolonged exposure may cause silicosis, bronchitis, or other chronic respiratory conditions	Use dust suppression, apply in low-wind conditions, provide PPE, and ensure enclosed or ventilated equipment for workers
Agricultural Disruption	ERW can alter soil pH, nutrient balance, or texture, potentially affecting crop growth and yields	Low to medium; impacts depend on crop type, soil conditions, and application rate	Conduct field trials; tailor application rates; monitor soil chemistry; engage farmers in planning and feedback

Effect of Enhanced Rock Weathering on Soil Organic Carbon

In addition to its impact on soil inorganic carbon, ERW may also influence soil organic carbon (SOC), a major pool of terrestrial carbon. The magnitude and direction of this influence remain subject of ongoing research and are likely to vary depending on local soil conditions and other factors. Whereas some studies suggest stabilization of SOC, others have documented SOC decreases as a result of ERW activity (Buss et al., 2024; Lei et al., 2025; Sokol et al., 2024). Several mechanisms may mediate ERW's effect on SOC, including changes in soil pH, microbial respiration rates, plant productivity, and physical soil properties such as compaction. SOC concentrations often vary greatly within and between years, compared to the variability of SIC. Because of the potential volatility of SOC and the resulting different storage permanence compared to SIC, carbon crediting based on SOC changes resulting from ERW is currently not a viable option (Mills et al., 2024). Soils with very high SOC concentrations (e.g., >5 wt% SOC, (Mills et al., 2024)) should be deprioritized for ERW project development in favor of less organic-rich soils to decrease the risk of SOC loss offsetting CDR.

4.5.1. The CO_2 removal supplier shall monitor soil organic carbon (SOC) concentrations on field sites throughout the crediting period on samples taken at least before or at the start of each monitoring period (see also rule 9.4.4 and table 9.2). If a statistically significant and sustained (i.e., persisting over >1 year) SOC reduction in application sites compared to control sites is observed, counter-measures (e.g., reduction of feedstock application) shall be considered to avoid long-term, significant SOC loss in future deployments. SOC reduction also falls under embodied emission treatment, see rule 7.4.4.

Heavy metals

Heavy metals in ERW feedstocks—such as nickel, chromium, or cobalt—have the potential to pose ecological and human health risks if mobilized into soil or water. In plants, elevated concentrations can inhibit growth and nutrient uptake. In soils, they may harm microbial communities and reduce fertility. If leached into groundwater or absorbed by crops, they can enter food chains, posing risks to animals and humans through bioaccumulation. Some, like hexavalent chromium, are toxic and carcinogenic even at low concentrations. The severity depends on metal concentration, rock weathering rate, soil properties, and local hydrology. In order to mitigate these risks, feedstocks and their applications will be subject to limitations and regulations laid out in this section.

Heavy metal concentrations in the weathering material

Heavy metal concentration in applied weathering materials shall be evaluated and reported to ensure they are consistent with local regulations and do not pose environmental or health risks.

4.5.2. The CO_2 Removal Supplier shall test their feedstocks and report on the concentrations of the PTEs listed in table 4.3).

4.5.3. The CO_2 Removal Supplier shall ensure that the concentrations of heavy metals and other PTEs in weathering material, including all the elements listed in table 4.3, complies with all local and jurisdictional regulations.

Maximum heavy metal concentrations in the soil

Evaluating heavy-metal risks in ERW projects using threshold values from maximum concentrations in soils requires measurement of background (pre-project) concentration levels as well as the post-application thresholds within the soil (rule 9.4.4, table 9.2).

4.5.4. CO_2 Removal Suppliers shall test the soils within their project and report on the concentrations of the PTEs listed in table 4.3.

4.5.5. Limit values for heavy metals in soil (listed in table 4.3) should not be exceeded at the field site before or after feedstock application. Elements without an identified limit shall also be evaluated and reported.

4.5.6. The CO_2 Removal Supplier shall demonstrate with appropriate statistical tests at >95% confidence level the mean concentration of a given heavy metal is below its applicable (see rules 4.5.7 to 4.5.10) limit value.

Table 4.3. Limit values for metal contents in soils derived from Council Directive 86/278/EEC of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture and Regeling Bodemkwaliteit 2022. DM: dry matter.

Metal	Limit (mg/kg DM)
Antimony (Sb)	2
Arsenic (As)	5
Barium (Ba)	-
Beryllium (Be)	-
Cadmium (Cd)	1
Chromium (Cr)	100
Cobalt (Co)	20
Copper (Cu)	100
Lead (Pb)	60
Manganese (Mn)	-
Mercury (Hg)	0.5
Nickel (Ni)	150
Selenium (Se)	-
Thallium (Tl)	-
Uranium (U)	-
Vanadium (V)	100
Zinc (Zn)	200

4.5.7. CO_2 Removal Suppliers operating in regions with more stringent requirements shall comply with all limits and regulations pertaining to their locale.

4.5.8. CO_2 Removal Suppliers who are operating in the United States or another area with less stringent limits for heavy metals in soil should operate within the limits proscribed in table 4.3 above.

4.5.9. In cases where CO_2 Removal Suppliers are compliant with the regulatory limits of their region, but remaining below the limits proscribed in table 4.3 is not feasible, a contextual justification may be provided to indicate why soil concentrations exceed the limits and the risk mitigation efforts being undertaken.

4.5.10. Projects that exceed the proscribed PTE limits in soils after the application of soil amendments, but incorporate mitigation strategies, may be permissible. These projects should demonstrate compliance with the limits listed in table 4.3 by the end of the monitoring period.

Asbestos

Asbestos is the general name given to naturally fibrous silicate minerals occurring in 'asbestiform' crystals that can cause serious human health risks via exposure through inhalation. The most common type of asbestos minerals belongs to the serpentine group, namely chrysotile (white asbestos), but asbestos can also occur in rocks which contain minerals from the amphibole group including amosite, crocidolite, and tremolite.

In ERW projects, exposure to asbestos or asbestiform minerals may happen during handling or spreading of the weathering material, as well as after application through wind erosion. In ERW projects, grinding and comminution of the weathering material may be necessary, and it can thereby be conservatively concluded that weathering material should not contain asbestos or asbestiform minerals above trace levels.

4.5.11. CO_2 Removal Suppliers using ultramafic rocks such as serpentinite and peridotite or rock containing amphibole minerals shall screen their feedstocks for the presence of asbestos.

4.5.12. Asbestos screening shall use Polarized Light Microscopy (PLM) or Transmission Electron Microscopy (TEM) or Scanning Electron Microscopy (SEM) to detect asbestos fibers. This may be aided by XRD and Thermogravimetric Analysis (TGA) or Differential Thermal Analysis (DTA). The acceptable limit shall be $\leq$ 0.25% by weight[34].

Radionuclides

Radionuclides are naturally present in the environment, in soil, and in some weathering material. Excessive exposure to radionuclides affects human health. Application of weathering material with high levels of radionuclides might lead to increased concentrations in soils.

4.5.13. CO_2 Removal Suppliers using feedstocks that originate from phosphate rocks, granite, pegmatites, tectonically altered or volcanic rocks, mine tailings or industrial byproducts shall screen for the presence of radionuclides.

4.5.14. Radionuclides screening shall be performed via gamma spectroscopy or ICP-MS to measure:

- Uranium (U-238 series)
- Thorium (Th-232 series)
- Potassium-40 (K-40)

4.5.15. The acceptable limit of radionuclides in feedstock material shall be <1 kBq/kg.[35]

---

[34] California EPA: Air Resources Board Test Method 435 Determination of Asbestos Content of Serpentine Aggregate

[35] Commission Delegated Regulation (EU) 2022/973 -Article 2.2 - laying down criteria on agronomic efficiency and safety for the use of by-products in EU fertilising products

Other PTEs

4.5.16. CO_2 Removal Suppliers using feedstocks that may have been exposed to chemicals or other treatments which may pose risk to biological organisms or ecosystems shall conduct appropriate chemical analyses of the possible contaminants in the feedstock and comply with local regulations to minimize the risk.

Respiratory risk from dust inhalation

ERW involves grinding and spreading rocks, which can generate fine particulate dust (e.g., PM_{10} and $PM_{2.5}$). Inhalation of this dust—especially if it contains crystalline silica (quartz)—can pose significant respiratory risks. Chronic exposure may lead to silicosis, bronchitis, or other lung diseases, particularly for workers involved in crushing, handling, and field application.

The general public's risk is low if dust is well-contained, but improper application—especially under dry or windy conditions—can create localized air quality concerns. Risk is elevated in fine particle size ranges (under 100 µm), which are common in ERW to speed weathering.

Mitigation measures include using low-dust formulations, applying under damp conditions, enforcing PPE for workers, and selecting feedstocks with verified low hazard profiles. Dust control is critical for both worker safety and community acceptance of ERW projects.

4.5.17. CO_2 Removal Suppliers shall comply with mitigation measures prescribed in ISO 45001[36] pertaining to dust and inhalation hazards including the applicable hazard identification, risk assessment, risk mitigation, worker participation, monitoring and evaluation protocols.

---

[36] ISO. (2018). ISO 45001:2018 Occupational health and safety management systems *Hazard identification for dust inhalation: Clause 6.1.2.1. Risk assessment of airborne dust exposures: Clause 6.1.2.2. Controls for dust hazards: Clause 8.1.2. Monitoring of workplace dust exposure: Clause 9.1*

5. Quantification of CO_2 Removal Certificates (CORCs)

5.1. General principles

In general, a CORC represents net 1 tonne CO_2e removed from the atmosphere. In the specific case of Enhanced Rock Weathering, the CO_2 removal results from the chemical reactions occurring during the weathering process, which remove CO_2 from the atmosphere and sequester it as long-lasting solid or dissolved mineral substances (mainly bicarbonates and carbonates).

The overall principle of the CORC calculation (see figure 5.1) is that the CO_2 Removal Supplier first determines the gross amount (in metric tonnes) of CO_2 sequestered as a result of the weathering reactions over a given monitoring period. Various deductions are then made, such as supply chain *emissions*, any potential *losses,* and the effect of any potential economic *leakage*. The resulting net amount of carbon sequestered is converted to CO_2 equivalents and credited as CORCs. More details on the method of calculation are given in this section.

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

	CORCs	C_{stored}	C_{baseline}	C_{loss}	E_{project}	E_{leakage}
Description	Net amount of CO_2e removed by the ERW activity during the reporting period.	Gross amount of CO_2e stored via weathering of applied feedstock material	Total amount of CO_2e which would have been stored in the absence of the removal activity.	Total GHG re-emissions during the storage period.	Total life cycle emissions arising from the whole supply chain of the ERW activity.	Total indirect GHG emissions resulting from unmitigated negative impacts associated with the ERW 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. CORC calculation equation (excluding uncertainty correction, see equation 5.1).

5.2. Requirements for robust quantification of net carbon removal

5.2.1. Continued in-field measurements are required from the CO_2 Removal Supplier in order to quantify the amount of CO_2 sequestered (section 6, section 11.2).

5.2.2. The CO_2 Removal Supplier shall meter, quantify, and keep records of the parameters needed to quantify the CO_2 removal. This includes, but is not limited to, the quantity of weathering material extracted and applied, the direct use of energy and fuels, and other greenhouse gas emissions from the process. These data must in particular be available to the Auditor, for the Production Facility Audit and Output Audits.

5.2.3. The CO_2 Removal Supplier shall assure the quality of measurements by applying appropriate quality control systems and procedures (section 10.3). This includes but is not limited to proper instrument calibration and data recording in reliable data systems.

5.2.4. The CO_2 Removal Supplier shall provide a written description of the approach used to quantify the weathering process and the expected carbon removal, in accordance with the requirements defined in this methodology. The description shall encompass both empirical quantification as well as any site-specific modeling (if applicable) of the weathering process (section 9).

5.2.5. Based on the results of an LCA analysis (section 7) and a scientifically justified estimation of the expected carbon removal over time, the CO_2 Removal Supplier must be able to present a net-negative overall carbon footprint for the cradle-to-grave activity, for eligibility of the ERW activity.

5.2.6. The CO_2 Removal Supplier shall quantify the overall uncertainty of the net CO_2 removal activity based on the combined uncertainty of the components included in equation 5.1 (see section 10.5).

5.2.7. The CO_2 Removal Supplier shall calculate the amount of sequestered carbon in the form of CO_2 Removal Certificates (CORCs) for each monitoring period, as per the requirements detailed in this Methodology.

5.2.8. 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 Enhanced Rock Weathering activity.[37] These records shall include time stamped, quantitative information such that their effect on the Output volume of the monitoring period can be quantified. These records shall be available to the Auditor, for the Production Facility Audit and Output Audits.

5.3. Overall equation

5.3.1. 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 table 5.2 for descriptions of the variables and figure 5.1 for an illustration):

$$CORCs = F_c\, x\, (C_{stored} - C_{baseline} - C_{loss} - E_{project} - E_{leakage}) \qquad (5.1)$$

Table 5.2. Descriptions and units of the variables in the CORC equation.

Variable	Description	Unit
$CORCs$	Net amount of CO_2 equivalents removed by the enhanced weathering activity.	tCO_2e

---

[37] 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).

Variable	Description	Unit
F_c	Factor of conservativeness calculated based on the total uncertainty in the net CO_2 removal activity in accordance with the requirements in section 10.5 (see in particular rule 10.5.3)	unitless
C_{stored}	Gross amount of CO_2 stored via weathering of the applied rock in the application sites. Further requirements on the calculation of this term are given in section 6.1.	tCO_2e
$C_{baseline}$	Gross amount of CO_2 stored via natural weathering in the control sites and via natural weathering of the untreated weathering material. Further requirements on the calculation of this term are given in section 6.2.	tCO_2e
C_{loss}	Total re-emissions or losses of the sequestered CO_2 as a result of subsequent biological uptake or chemical reactions in the environment following the initial weathering. Further details and 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
$E_{leakage}$	The amount of CO_2-eq emitted indirectly due to unmitigated negative ecological, market, and activity-shifting leakage resulting from the Enhanced Rock Weathering activity. Further requirements on the calculation of this term are given in section 8.	tCO_2e

The subsequent sections of this Methodology will follow eq. 5.1 by describing how C_{stored}, $C_{baseline}$, and C_{loss} (section 6), project emissions ($E_{project}$, section 7), and indirect emissions ($E_{leakage}$, section 8) are determined. This is followed by section 9, which describes the monitoring program necessary for this, and section 10, which describes the sampling, measurements, and uncertainty quantification underlying this monitoring program.

6. Determination of stored carbon, baseline carbon removal, and carbon loss

6.1. Carbon stored (C_{stored})

The term C_{stored} describes the gross amount of carbon dioxide sequestered into carbonate and bicarbonate ions through weathering of the applied material and exported from the NFZ to the FFZ. It also includes any precipitation of solid carbonate minerals (pedogenic carbonates) within the NFZ (section 1.5, section 11.2).

6.1.1. The quantification of C_{stored} shall be based on measurement of weathering signals at the application site using quantification and validation approaches (see rule 9.5.2) as described in section 11.2 and summarized in table 6.1.

6.1.2. The weathering signal at the application sites shall be measured at least at the beginning (t_0) and end (t_1) of a monitoring period in order to calculate C_{stored} as appropriate for the applied quantification approach (see eqs. 11.2-11.35, section 11.2).[38]

6.1.3. Weathering signals shall be converted into removed carbon dioxide based on the stoichiometry of the underlying chemistry. The calculations (eqs. 11.2-11.35) described in section 11.2 for the relevant quantification approach shall be followed depending on the chosen quantification approach. For example, if cations leached from the NFZ are used as the weathering signal, for each mole-equivalent cation charge lost from the NFZ, 1 mol of CO_2 is sequestered (eq 1.1). For carbonate mineral formation within the NFZ that is a consequence of the Enhanced Rock Weathering activity, 1 mol CO_2 captured per 1 mol $CaCO_3$ formed shall count toward C_{stored} for carbonate mineral formation subsequent to silicate weathering (eq. 1.4).

---

[38] Note that measurement time points between t_0 and t_1 will be referred to as $t_{0.1}$, $t_{0.2}$, etc. in this methodology but this is simply an illustrative measure that does not indicate any maximum allowable or recommended number of measurement time points.

Table 6.1. Overview of quantification and validation approaches for C_{stored} measurements and applicable NFZ loss terms (section 6.3). Note that the FFZ loss terms Loss_{river} and Loss_{ocean} apply to each approach.

Type	Approach	Description	Applicable loss terms	Scientific reference	Quantification or validation
Soil	A1 - CAT_{WM}	Tracking weathering material	Loss_{plant}, Loss_{acid}, (Loss_{adsorb}^{*}, $\text{Loss}_{carbonate}^{*}$, $\text{Loss}_{silicate}^{*}$)	Reershemius et al., 2023	Quantification/ validation
	A2 - CAT_{Ti}	Tracking weathering material and immobile trace elements	Loss_{plant}, Loss_{acid}, (Loss_{adsorb}^{*}, $\text{Loss}_{carbonate}^{*}$, $\text{Loss}_{silicate}^{*}$)	Reershemius et al., 2023	Quantification/ validation
Water	A3 - $\text{CAT}_{porewater}$	Tracking cations dissolved in soil pore water	Loss_{acid} (Loss_{plant}^{**}, $\text{Loss}_{adsorb}^{**}$, $\text{Loss}_{carbonate}^{**}$, $\text{Loss}_{silicate}^{**}$)	Amann et al. 2020	Quantification/ validation
	A4 - $\text{BIC}_{porewater}$	Tracking of bicarbonate + carbonate ions in soil pore water as alkalinity (4a) or DIC (4b)	(Loss_{plant}^{**}, $\text{Loss}_{adsorb}^{**}$, $\text{Loss}_{carbonate}^{**}$, $\text{Loss}_{silicate}^{**}$)	Amann et al., 2022; McDermott et al., 2024	Quantification/ validation
	A5 - CAT_{resin}	Tracking cations sorbed into a resin (from pore water)	Loss_{acid} (Loss_{plant}^{**}, $\text{Loss}_{adsorb}^{**}$, $\text{Loss}_{carbonate}^{**}$, $\text{Loss}_{silicate}^{**}$)	-	Validation
Soil carbonate	A6 - SIC_{soil}	Tracking cations reprecipitated as calcium carbonate	-	Haque et al., 2020; Haque, Santos, et al., 2019; Jariwala et al., 2022; Khalidy et al., 2021	Quantification

* Loss term applicable only if soil sample does not integrate across the full vertical extent of the NFZ.
** Loss term applicable only if water sampling occurs above the base of the NFZ.

6.2. Baseline ($C_{baseline}$)

$C_{baseline}$ represents an estimate of the carbon dioxide sequestration that would have occurred without the ERW activity. It has two components: a) $C_{baseline\text{-}[feedstock]}$, the counterfactual weathering of feedstock had it not been spread out on fields by the CO_2 removal supplier; b) $C_{baseline\text{-}[field]}$, the carbonic-acid weathering in application site soil that would have naturally occurred without the ERW activity. As such, $C_{baseline}$ is equivalent to the "counterfactual" or the "business-as-usual" scenario (see also section 11.1).

Thus, $C_{baseline}$ can be calculated as follows:

$$C_{baseline} = C_{baseline-[field]} + C_{baseline-[feedstock]} \tag{6.1}$$

Where:

Variable	Description	Unit
$C_{baseline-[field]}$	Field-component of baseline CO_2 sequestration associated with the ERW activity. It is measured as the weathering signal at control sites.	tCO_2e
$C_{baseline-[feedstock]}$	Feedstock-component of baseline CO_2 sequestration associated with the ERW activity. It represents the CO2 that would have been sequestered by weathering of the feedstock material without the ERW activity.	tCO_2e

Counterfactual in-field weathering $C_{baseline-[field]}$

6.2.1. Control sites (see section 11.1) shall be used to determine $C_{baseline-[field]}$, i.e., the in-field component of $C_{baseline}$, which also includes counterfactuals such as agricultural liming.

6.2.2. The quantification of $C_{baseline-[field]}$, shall be based on measurement of weathering signals at the control site using quantification approaches as described in section 11.2 and summarized in table 6.1.

6.2.3. The weathering signal at the control sites shall be measured at least at the beginning (t_0) and end (t_1) of a monitoring period in order to calculate $C_{baseline-[field]}$ as appropriate for the applied quantification and validation approach (see eqs. 11.2-11.35, section 11.2). The same quantification and validation approaches shall be used on control sites as on the corresponding application sites.

Counterfactual feedstock weathering $C_{baseline-[feedstock]}$

In addition to baseline weathering occurring on the field site, $C_{baseline}$ includes counterfactual weathering of rock material that would have occurred had the rock material not been treated (e.g., ground) and spread out on the application sites as feedstock, $C_{baseline-[feedstock]}$.

6.2.4. The CO_2 removal supplier must present an estimate of $C_{baseline-[feedstock]}$, defined as the amount of CO_2 (in tonnes) that the weathering material utilized in the project would have naturally sequestered over the course of 50 years following the start of the ERW activity, had the activity not occurred. The estimate must be conservative and be based on information gathered from either the CO_2 Removal Supplier's own scientific research or peer-reviewed scientific publications.

6.2.5. The estimate shall consider at least the effect of three (3) factors to the sequestration rate represented by $C_{baseline-[feedstock]}$: mineralogy, physical form (including particle size) and likely storage conditions (including ambient CO_2 concentrations). The sequestration amount shall be estimated based on the physical form of the material (e.g. solid mineral, ground particles, or fine dust) it would have been in without the project's activities.

6.2.6. To perform the estimate, the CO_2 removal supplier may utilize e.g. average sequestration rates from scientific literature that are applicable to the external conditions under consideration. A full chemical kinetics simulation is not required.

6.2.7. The CO_2 Removal Supplier must utilize reasonable, conservative assumptions for variable factors such as likely storage conditions during the estimation period.

6.2.8. The baseline estimate shall include a discussion of the level and sources of uncertainty in the amount of CO_2 sequestered.

6.2.9. The baseline estimate shall only consider the effect of natural CO_2 sequestration of the feedstock material. Specifically, no deductions due to e.g. avoided emissions or any other project activities may be included. The baseline sequestration amount can therefore never be negative.

6.2.10. For inert feedstock materials, the baseline estimate and its effects on the amount of CORCs can be ignored in cases where it is scientifically reasonable to assume that the amount of CO_2 sequestered naturally by the material would be 1 % or less of the total amount sequestered by the project. However, it shall be the responsibility of the CO_2 Removal Supplier to present scientific evidence to support such an assumption.

6.2.11. The CO_2 Removal Supplier must present its baseline estimate and the underlying assumptions and sources thereof to Puro experts for review. The reliability of the estimate shall be at the discretion of Puro experts.

6.2.12. Projects, where the baseline sequestration amount is estimated to be 50 % or more of the total amount sequestered are not eligible to be credited under the Enhanced Rock Weathering methodology.

Eligibility threshold with respect to $C_{baseline}$

6.2.13. For CORCs to be issued for a given monitoring period, C_{stored} must exceed $C_{baseline}$ to a statistically significant degree. The CO_2 Removal Supplier shall demonstrate statistical significance using appropriate inferential statistical tests (e.g. t-test) to test the null-hypothesis that no weathering occurred.

6.3. Carbon losses (C_{loss})

C_{loss} represents feedstock loss to non-carbonic weathering processes (see section 1.5) and biogeochemical processes that reverse initial carbon dioxide sequestration caused by the added weathering material.

6.3.1. The CO_2 Removal Supplier shall identify, quantify and account for all relevant loss (re-emission) pathways. The set of relevant loss pathways (see section 1.5) shall at least include:

- $Loss_{acid}$: Weathering of rock feedstock by acids other than carbonic acid ("non-carbonic acid weathering" aka "strong-acid weathering") - (NFZ)

- Loss$_{plant}$: Plant uptake of major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) - (NFZ)
- Loss$_{adsorb}$: Cation adsorption onto soil particles - (NFZ)
- Loss$_{carbonate}$: Secondary carbonate mineral formation - (NFZ)
- Loss$_{silicate}$: Secondary silicate mineral formation - (NFZ)
- Loss$_{rivers}$: Losses from surface freshwater systems (e.g. rivers, lakes) - (FFZ)
- Loss$_{ocean}$: Losses from marine systems (e.g. seas, oceans)- (FFZ)

6.3.2. The total greenhouse gas emissions due to loss pathways (C_{loss}) shall be calculated for each applicable loss pathway as described in rules 6.3.3-6.3.11. First, applicable loss terms based in the NFZ shall be summed up as follows to derive $C_{loss-NFZ}$:

$$C_{loss-NFZ} = \sum_{i \in S} mCO_2e_i \tag{6.4}$$

Next, the FFZ-based loss terms shall be applied to the NFZ-loss corrected sequestration sequentially as follows to derive $C_{loss-FFZ}$:

$$C_{loss-FFZ} = (C_{stored} - C_{baseline-[field]} - C_{loss-NFZ}) \times (1 - \prod_{i \in R} [1 - F_i]) \tag{6.5}$$

Finally, the calculated losses from NFZ and FFZ shall be summed up as follows:

$$C_{loss} = C_{loss-NFZ} + C_{loss-FFZ} \tag{6.6}$$

Table 6.2. Descriptions and units of the equations for loss pathways (eqs. 6.4 - 6.6).

Variable	Description	Unit
C_{loss}	Total losses of the sequestered CO_2 as a result of subsequent chemical reactions in the environment following the initial weathering.	tCO_2e
$C_{loss-NFZ}$	Losses of sequestered CO_2 as a result of subsequent chemical reactions in the NFZ following the initial weathering. Includes loss from the pathways Loss$_{acid}$, Loss$_{plant}$, Loss$_{adsorb}$, Loss$_{carbonate}$, and Loss$_{silicate}$ as applicable.	tCO_2e
$C_{loss-FFZ}$	Total losses of the sequestered CO_2 as a result of subsequent chemical reactions in the FFZ following the initial weathering. Includes loss from the pathways Loss$_{rivers}$ and Loss$_{ocean}$.	tCO_2e
mCO_2e_i	Total mass of GHGs emitted from NFZ loss pathway i	tCO_2e
F_i	Percentage loss factor associated with the FFZ loss pathway i (either riverine or ocean losses), calculated as a percentage of the sequestered carbon entering the FFZ (i.e. [C_{stored} - $C_{baseline-[field]}$ - $C_{loss-NFZ}$])	%
i	Summation index (an element in the set of loss pathways S or R)	unitless
S	The set of relevant loss pathways from the NFZ (Loss$_{acid}$, Loss$_{plant}$, Loss$_{adsorb}$, Loss$_{carbonate}$, Loss$_{silicate}$)	unitless
R	The set of relevant loss pathways from the NFZ (Loss$_{rivers}$, Loss$_{ocean}$).	unitless

6.3.3. The CO_2 Removal Supplier shall quantify the total amount of CO_2 released from each applicable loss pathway (mCO_2e_i for NFZ-losses, or F_i for FFZ-losses, see rule 6.3.2) through measurement, modeling, or conservative estimation as further detailed in rules 6.3.4-6.3.11. Applicable loss pathways for each C_{stored} quantification approach are listed in table 6.1. FFZ-loss pathways always apply. For NFZ-loss pathways that are inapplicable to the utilized quantification approach, no measurements or estimations are necessary and the value $mCO_2e_i = 0\ \mathrm{tCO_2e}$ shall be utilized.

6.3.4. For the loss pathway **non-carbonic acid weathering ($\mathbf{Loss_{acid}}$)**, the CO_2 Removal Supplier shall quantify the value of mCO_2e_i through one of the following means:

a. Direct measurement of the concentrations of major anions in soil porewater (e.g. via ion chromatography, ISO 10304-1:2007) from the NFZ combined with an estimate of the total volume of water infiltrated into the soil (soil water flux, F_{sw}).

  i. The monitored major anions shall include nitrate (NO_3^-), phosphate (PO_4^{3-}), chloride (Cl^-), sulfate (SO_4^{2-}), as well as any other anions that are or can reasonably be considered as relevant to local soil chemistry, land management practices, and the weathering material utilized.

  ii. Anion concentration estimates shall be based on samples taken at least at the beginning (t_0) and end (t_1) of the monitoring period at the base of the NFZ (see rule 11.2.9-11.2.13) using appropriate sampling methodology (section 11.1).

  iii. If initial screening at a given site indicates undetectable concentrations of any anion, future measurements may exclude those anions from analysis provided an absence of relevant environmental and agronomic changes, especially fertilizer application.

  iv. Concentrations of a given anion (*i*) measured across a monitoring period on a given application or control site shall be averaged (C_i) and multiplied with the charge (*n*) of the given anion and the soil water flux estimate (F_{sw}, see also information box 1) to estimate the non-carbonic acid loss represented by the vertical anion export flux ($F_{acid\text{-}loss}$) out of the NFZ of the set of anions (*S*, including nitrate, phosphate, chloride, sulfate) in the following way, separately for control (*contr*) and application (*appl*) sites:

$$F_{acid-loss}[contr] = \sum_{i\in S}(C_i \times n_i \times F_{sw} \times MW_{CO2}/MW_{AN_i}/10^6) \tag{6.7}$$

$$F_{acid-loss}[appl] = \sum_{i\in S}(C_i \times n_i \times F_{sw} \times MW_{CO2}/MW_{AN_i}/10^6) \tag{6.8}$$

  v. Then, the conservative assumption shall be made that each negative anion charge exported was balanced by the positive charge of a cation after weathering, representing non-carbonic acid weathering. Based on this, the net carbonic-acid weathering rate in the control sites ($C_{baseline\text{-}[field]}$) may be reduced by the estimated non-carbonic acid weathering rate on control sites but only to the point where $C_{\text{baseline-[field]}}$ still remains ≥0 following this correction. This control-site estimate may then be subtracted from the parallel estimate of non-carbonic acid weathering on corresponding application sites. The resulting, control-site corrected non-carbonic acid weathering estimate shall then be used as the value for mCO_2e_i representing $\mathbf{Loss_{acid}}$:

$$mCO_2e_{Loss-acid} = (F_{acid-loss}[appl] - F_{acid-loss}[contr]) \times t \times A \qquad (6.9)$$

If the calculation in eq. 6.9 results in a negative value, $mCO_2e_{Loss-acid}$ shall equal zero.

Table 6.3. Descriptions and units of the equations for the non-carbonic acid-loss pathway (eqs. 6.7 - 6.9).

Variable	Description	Unit
C_i	Measured concentration (average across monitoring period) of a given anion *i*	mol L^{-1}
n_i	Charge of a given anion *i* (e.g., 2 for SO_4^{2-}, 1 for NO_3^-)	-
S	The set of anions measured and taken into account for non-carbonic acid accounting, normally including nitrate, sulfate, phosphate, and chloride.	-
F_{sw}	Soil water flux estimate	L m^{-2} yr^{-1}
MW_{CO2}	The molecular weight of CO_2	g/mol
MW_{AN_i}	The molecular weight of a given anion *i*	g/mol
$F_{acid-loss}[j]$	Non-carbonic acid loss represented by the vertical anion export flux from the NFZ, where *j* = application site (*appl*) or control site (*contr*).	*tCO2e* *m^{-2} yr^{-1}*
t	Duration of the monitoring period	*yr*
A	Application site area represented by this calculation	*m^2*
$mCO_2e_{Loss-acid}$	Total mass of GHGs emitted from NFZ loss pathway $Loss_{acid}$	tCO_2e

b. Indirect measurement of the concentrations of major anions in soil porewater combined with an estimate of the total volume water infiltrated into the soil. Such indirect estimates may be derived by subtracting [bicarbonate+carbonate] concentrations from cation concentrations after measuring each in porewater. The result of this subtraction may be assumed to represent major anions representing non-carbonic acidity, provided that the same requirements set above for direct anion concentration measurements are met, specifically sampling time points and comparison between control and application site.

c. A conservative estimation following the approach outlined by Dietzen & Rosing (2023) for determining the proportion of weathering by sources of acidity other than carbonic acid via a calculation of the carbonate system speciation based on any two parameters from the carbonate system measured in the soil. A conservative estimate of pCO_2 = 1000 µatm (Dietzen & Rosing, 2023) may be used instead of measuring this parameter.

6.3.5. For the loss pathway **plant uptake of major cations ($Loss_{plant}$)**, the CO_2 Removal Supplier shall quantify the value of mCO_2e_i through direct measurement of the total base cation content of above-ground plant biomass (e.g., by EPA Method 3050B, AOAC Official Method 975.03, ICP-MS (ISO 17294-1:2024), or ICP-OES (ISO 11885:2007) after digestion) coupled with an estimate of the total plant biomass yield of the the field.

a. This quantification of the loss shall be done separately for control sites and application sites and the value for **$Loss_{plant}$** determined on control sites shall be subtracted from the value for **$Loss_{plant}$** determined on application sites in order to quantify mCO_2e_i. If **$Loss_{plant}$** on control sites is greater than on application sites, the value for mCO_2e_i shall be zero.

b. For annual crops, plant samples shall cover the entire portion of the plant (typically the entire above-ground portion, but also the below-ground portion if actively removed from soil samples for C_{stored} quantification) that contains cations that have escaped sampling for C_{stored} quantification by incorporation into plant biomass. For perennial crops, the plant samples shall cover new growth that occurred during the monitoring period combined with an estimate of the net new biomass (Battles et al., 2014).

6.3.6. The loss pathway of **adsorbed cations within the NFZ ($Loss_{adsorb}$)** describes cations adsorbed to surface sites of soil particles, preventing their export from the NFZ. Of the C_{stored} quantification approaches described in section 11.2, none will create a false positive signal caused by cations adsorbed within the NFZ if sampling covers the entire NFZ. Therefore, the value $mCO_2e_i = 0\ \mathrm{tCO_2e}$ may be utilized except under circumstances that require a **$Loss_{adsorb}$** correction, which include:

- Soil water samples for C_{stored} measurements taken above the base of the NFZ: **$Loss_{adsorb}$** corrections are necessary for the portion between sampling depth and base of NFZ.
- Bulk soil samples for C_{stored} measurements that do not integrate over the entire vertical extent of the NFZ: **$Loss_{adsorb}$** corrections are necessary for the portion of the NFZ not covered by the samples.
- If exchangeable cations are flushed from samples for C_{stored} quantification via measurement of cation decrease from bulk soil (CAT_{WM}, CAT_{Ti}) prior to analysis using mild extractants such as ammonium acetate.

See table 6.1 for the C_{stored} quantification approaches that may require this correction. If a **$Loss_{adsorb}$** correction is necessary, the value of $mCO_2e_{Loss-adsorb}$ shall be determined by the quantification of exchangeable cations after soil extractions with mild extractants (e.g., ammonium nitrate, ammonium acetate) and following peer-reviewed or standard protocols, including ISO 23470:2018, ISO 11260:2018, Dietzen et al. (2018), and Kelland et al. (2020). The value for $mCO_2e_{Loss-adsorb}$ shall derive from subtracting the increase in exchangeable cation charges during the monitoring period (from t_0 to t_1) in control site samples from the increase in parallel application site samples. If this subtraction results in a negative value, $mCO_2e_{Loss-adsorb}$ shall equal zero. It should be noted that cation adsorption can significantly delay the cation export from the NFZ and therefore monitoring it may be recommendable even if it does not interfere with carbon accounting (Kanzaki et al., 2025).

6.3.7. The loss pathway **secondary carbonate mineral formation ($\mathbf{Loss_{carbonate}}$)** describes the loss of 1 mol CO_2 per mol $CaCO_3$ (or equivalent carbonate mineral) formed inside the NFZ (see eq. 1.6). Of the C_{stored} quantification approaches described in section 11.2, none will create a false positive signal caused by secondary carbonate precipitation if sampling covers the entire NFZ. Therefore, the value $mCO_2e_i = 0\,\mathrm{tCO_2e}$ may be utilized except under circumstances that require a $\mathbf{Loss_{carbonate}}$ correction, which include:

- Soil water samples for C_{stored} measurements taken above the base of the NFZ: $\mathbf{Loss_{carbonate}}$ corrections are necessary for the portion between sampling depth and base of NFZ.
- Bulk soil samples for C_{stored} measurements that do not integrate over the entire vertical extent of the NFZ: $\mathbf{Loss_{carbonate}}$ corrections are necessary for the portion of the NFZ not covered by the samples.
- If exchangeable cations are flushed from samples for C_{stored} quantification via measurement of cation decrease from bulk soil (CAT_{WM}, CAT_{Ti}) prior to analysis using mild extractants such as ammonium acetate. This practice may partially dissolve calcite and so its employment warrants quantification of SIC decrease (falsely indicating additional cation loss from NFZ) in the soil sample as a result of this practice.

See table 6.1 for the C_{stored} quantification approaches that may require this correction. If a $\mathbf{Loss_{carbonate}}$ correction is necessary, the value of $mCO_2e_{Loss-carbonate}$ shall be determined by the quantification of soil inorganic carbon (SIC) from bulk soil samples taken just after feedstock application (t_0) and at the end of the monitoring period (t_1) using appropriate methods, including thermogravimetric analysis (TGA), calcimetry (ISO 10693:1995), or dry combustion (Leogrande et al., 2021; ISO 10694:1995). The value for $mCO_2e_{Loss-carbonate}$ shall derive from subtracting the increase in SIC during the monitoring period (t_0 to t_1) in control site samples from the SIC increase in parallel application site samples. If this subtraction results in a negative value, $mCO_2e_{Loss-carbonate}$ shall equal zero.

6.3.8. For the loss pathway **secondary silicate mineral formation ($\mathbf{Loss_{silicate}}$)**, the value $mCO_2e_i = 0\,\mathrm{tCO_2e}$ may be utilized. As of the writing of this document (10/2025), no operationally viable method is available to quantify this loss term (Mills et al., 2024). The CO_2 removal supplier should utilize sampling approaches that implicitly correct for this loss pathway, i.e., soil-water sampling at the base of the NFZ or bulk-soil sampling integrating the entire vertical extent of the NFZ (see also rule 11.1.11).

6.3.9. To assess the impact of the loss pathway **losses from surface freshwater systems** to their production facility (**Loss**$_{\textbf{rivers}}$), the CO_2 Removal Supplier shall assess its two components, *i) carbonate mineral formation*, and *ii) CO_2 degassing due to carbonate system equilibration* in rivers downstream from the field site and account for it as follows:

a. $SI_{calcite}$ (eq. 1.7), pH, and the share of CO_2 in DIC shall be quantified by appropriate measurements that include include at least temperature, pH, Ca^{2+} concentrations, and either DIC concentration or alkalinity based on samples taken at the following sites:

   1) Representative samples from tile drainages at sites with tile drainage systems.

   2) River water immediately (or as close as possible[39]) downstream of the field site. If different parts of a field site drain into different streams or rivers, samples shall be taken at least at the nearest point downstream where all these rivers meet but ideally additional samples should be taken also at the upstream branches closer to the field site outflows.

   3) In water from the catchment's highest-order river. $SI_{calcite}$ quantification in the highest-order river may be omitted if the catchment does not include areas dominated by carbonate lithology. If groundwater from a given field site drains directly into the ocean, the supplier shall measure $SI_{calcite}$ and the share of CO_2 in DIC in the coastal ocean water near the groundwater discharge site.

b. For these assessments, any available river water quality datasets of sufficient scientific quality (e.g., public monitoring program by the United States Geological Survey) containing data from samples taken ≤10 years before the start of the crediting period shall be analyzed. If such datasets do not exist for relevant sites, the CO_2 Removal Supplier shall take the necessary measurements using appropriate river water sampling and measurement approaches.

c. These datasets or measurements shall include at least two annual measurement points for each relevant parameter and at least two annual measurement points shall be from contrasting seasons defined by the local climatic zone: e.g., wet vs dry season in tropical climate, summer vs winter in temperate climate.

d. Based on these data, the values of F_i **Loss**$_{\textbf{rivers}}$ representing the carbonate mineral formation and CO_2 degassing components of the **losses from surface freshwater systems** loss term shall be determined as follows:

---

[39] In exceptional cases where legal (e.g., private property access) or physical (e.g., natural barriers like rapids or canyons) prohibit sampling immediately downstream of the field site, an accessible sampling site further downstream as close to the field site as possible shall be identified on a case-by-case basis and requires approval by the Issuing Body.

1) *If $SI_{calcite}$ <1.0 consistently at all downstream measurement points and seasons*, the supplier may either use a 5% conservative estimate for the value of **$\mathbf{Loss_{rivers}}$** (Zhang et al., 2025) or apply an appropriate model to estimate CO_2 evasion due to carbonate system equilibration in downstream river systems (e.g., Zhang et al. 2025) and use the resulting estimate to determine the value of **$\mathbf{Loss_{rivers}}$**.
2) *If pH* >6.5 *and $SI_{calcite}$ <1.0 consistently at all downstream measurement points and seasons*, the supplier may either use a 2.5% estimate for the value of **$\mathbf{Loss_{rivers}}$** (Zhang et al., 2025) or apply an appropriate model to estimate CO_2 evasion due to carbonate system equilibration in downstream river systems (e.g., Zhang et al. 2025) and use this estimate to determine the value of **$\mathbf{Loss_{rivers}}$**.
3) *If $SI_{calcite}$ >1.0 consistently at one or more downstream measurement points and seasons*, the supplier shall use the river dataset to estimate CO_2 loss from carbonate mineral formation in the river segment(s) represented by this measurement point, assuming equilibrium conditions. This estimate shall be added to a 2.5% estimate for the carbonate-system equilibration component to determine the value of **$\mathbf{Loss_{rivers}}$** in this case.
4) *If pH* ≤6.5 *consistently at one or more downstream measurement points and seasons,* the supplier shall use appropriate models (e.g., Zhang et al., 2025) to estimate CO_2 evasion due to carbonate system equilibration in downstream river systems. This estimate shall be used as the value of **$\mathbf{Loss_{rivers}}$** in this case.

Note: for the above assessments of $SI_{calcite}$ and pH in river water, “consistently” shall allow for the exclusion of individual measurement that can be deemed a random outlier either based on a measurement inaccuracy or based on statistical analysis compared to the available time series of measurements at a given location.

6.3.10. For the pathway **losses from marine systems** the value of F_i = **$\mathbf{Loss_{ocean}}$** shall equal the percentage loss due the decrease in carbon uptake efficiency ($\Delta C/\Delta A$) of the ocean given local seawater chemistry and is defined as follows:

$$Loss_{ocean} = ([1 - Loss_{river}] - \Delta C/\Delta A) \times (1 + f) \qquad (6.12)$$

Where *f* represents the percentage of carbonate in the applied feedstock (e.g., *f* = *1.0* for pure carbonate feedstock, *f* = *0.0* if carbonate is undetectable in feedstock) and $Loss_{river}$ represents the applicable river loss (percentage) determined based on rule 6.3.9.

To determine this efficiency, the CO_2 removal supplier shall use appropriate oceanographic data (e.g., from public databases or scientific publications) to solve for $\Delta C/\Delta A$ based on eq. 1.8. For these calculations:

- Equilibrium conditions shall be assumed;

- Ocean near-surface water data that best represents the seawater receiving the river water from the catchment containing the field site shall be the basis;
- Appropriate tools shall be used, such as CO2sys (E. Lewis & Wallace, 1998);
- The feedstock carbonate content shall be taken into account (factor *f* in eq. 6.12)

Alternatively, if the CO_2 removal supplier cannot assess the carbon uptake efficiency based on local oceanographic data, a conservative estimate of 10% shall be used to represent **losses from marine systems** for pure silicate feedstocks (Kanzaki et al., 2023; Renforth & Henderson, 2017). In mathematical terms, this shall be implemented by solving eq. 6.12 after substituting the term $\Delta C/\Delta A$ in eq. 6.12 with the value 0.9. Note that the correction for feedstock carbonate content (factor f, eq. 6.12) is also necessary when using this conservative estimate and reflects the finding that pure carbonate feedstock results in $Loss_{ocean}$ of approximately 20% (Kanzaki et al., 2023).

6.3.11. For any other potential loss pathways identified, besides those within the purview of rules 6.3.4-6.3.10, the CO_2 Removal Supplier shall provide a detailed description of the identified pathway and the method of quantification.

7. Determination of project emissions

7.1. Life cycle approach for the quantification of project emissions

7.1.1. The CO_2 Removal Supplier shall calculate the life cycle emissions resulting from the development and operations of the carbon removal activity using a cradle-to-grave modelling approach (i.e. upstream and downstream activities), and based on both:

- A life cycle assessment model (LCA model) of operational emissions (section 7.3), and
- A life cycle inventory (LCI) of embodied emissions (section 7.4).

The life cycle emissions shall cover the scope defined in the system boundaries (rule 7.2.2), adhere to the Monitoring Plan requirements (rule 9.2.2), and follow the general principles defined in ISO-14040/44 and the ISO-14064 series.

7.1.2. The CO_2 Removal Supplier shall calculate and report project emissions using eq. 7.1 as follows:

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

Variable	Description	Unit
$E_{project,\,MP}$	Lifecycle emissions associated with the operation of the project during the monitoring period (MP) and the amortized portion of the lifecycle's embodied emissions.	tCO_2e
$E_{ops,\,MP}$	Lifecycle operational emissions from materials and energy used by the project during the monitoring period.	tCO_2e
$E_{emb,\,MP}$	Amortized lifecycle embodied emissions associated with the production, use, and disposal of infrastructure and equipment assets and direct land use changes.	tCO_2e

7.1.3. The LCA model 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 spreadsheet LCA model using the template provided by Puro.earth or a similar spreadsheet as long as formulae and cell referencing are transparent.
- 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.

7.1.4. The CO_2 Removal Supplier shall include with the Project Description (PD) a description of the LCA model, including the operational life cycle inventory, outlining each emission source, detailing what it represents as required by the data collection requirements (see section 10.4), and including:

- Relevant activity data (AD) included in the monitoring plan (section 9.2), and how it will be monitored and measured, along with explanation of the application of a cut-off criteria from the monitoring process, if applicable (see rule 7.1.6).
- Emission factors (EF) chosen (see rule 7.1.8).

Use of data estimates in LCA models

7.1.5. The CO_2 Removal Supplier may leave out from the monitoring plan individual activities or emission sources that contribute less than 1% of total LCI emissions quantification and assign a conservative value in its place, in order to simplify the development of the LCA model and the data collection process and use data estimates in its place (see section 9.2), considering the following:

a. Identify which individual activities or emission sources do not require monitoring and measurement of activity data from the operational life cycle inventory (LCI) model, which includes the following steps that the CO_2 Removal Supplier shall take:
    - develop an inventory that lists all possible individual activities or emission sources for each unit process (see rule 7.2.2) and type of emissions sources (e.g. energy use, material use, waste treatment, direct emissions);
    - determine with the support of preliminary calculations which individual activities or emission sources are expected to represent less than 1% of the overall inventory emissions and will not change significantly during project operations;
    - select from the activities determined in the previous step those that would cover up to 5% of overall inventory emissions and assign fixed conservative activity values to those activities in order to exclude them from the monitoring process, but still account for them in the inventory calculation.

b. The selection of any activity or emission sources from the LCI that will be excluded from the monitoring process shall be documented 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.

c. The following elements are considered out-of-scope for the purposes of LCA modeling, and therefore do not need to be included in the LCA Model:
    - Site selection and feasibility studies, non-recurring R&D activities;
    - Staff transport (e.g., business travel and employee commuting);

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

Note 1: This criteria cannot be applied to all emissions sources, as certain sources are explicitly required to be monitored and reported regardless of their magnitude (see section 3).

Note 2: The determination of out-of-scope activities for the operational LCI aims at not discouraging CO_2 Removal Suppliers from developing robust quantification monitoring practices.

Modeling of secondary resources and cut-off criteria

7.1.6. If waste, recycled or post-consumer secondary resources are used as input to the activity (e.g. industrial waste materials such as slags or mine tailings), it is permissible and recommended to apply the cut-off system model approach[40] for waste, recycled and post-consumer secondary products in the LCA. Specifically, the environmental burdens from disposal of such 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.[41]

Changes to the LCA model during the crediting period

7.1.7. 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 operations of the Production Facility. 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.

Type of emission factors

7.1.8. 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.

---

[40] 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.

[41] 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: https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en#end-of-waste-criteria

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.

> **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.

Cooperation between operators for LCA

7.1.9. The CO_2 Removal Supplier shall coordinate data collection and LCA modeling with any external operators[42] to the level necessary to ensure compliance with this methodology and the Puro Standard requirements.

7.2. Scope of Project Emissions

7.2.1. The CO_2 Removal Supplier shall define the functional unit of the ERW activity by determining all process flows and emissions associated with the application to soil and weathering of one (1) metric tonne of weathering material, with specific material granulometry, and soil incorporation process and depth, for the purpose of removing CO2 from the atmosphere.

7.2.2. The **system boundaries** of the LCA model of the ERW activity shall include the three main unit processes represented in figure 7.1, and defined as follows:

a. **Sourcing of Feedstock:** This process includes e.g., the mining of rock (in case of natural weathering material use) and its processing for deployment on agricultural soils. It may consist of all operations required for extracting and processing the material to its final size and granulometry (crushing, grinding, milling), including infrastructure requirements, material and energy consumption, as well as waste treatment. This process terminates with crushed material ready for application at the processing location.

b. **Transport of Feedstock:** This process includes all operations required for supplying the ground material to its site of application, including loading, transportation, and unloading, as well as infrastructure requirements (road, truck, fuel supply-chain), when applicable and in alignment with the GLECv3.1 framework. This terminates with processed material ready for application at the site.

---

[42] Data required for performing the LCA of an ERW activity originates from multiple parties operating in the feedstock production (i.e., quarry), transportation, and on-site application.

c. **Application of Feedstock:** This process refers to all operations required for spreading and/or incorporation of the processed material to the site. This includes machinery and fuel use. This terminates with processed material applied and incorporated to the soil at the application location. In addition, this stage includes the period of weathering and carbon storage. However, the emissions associated with the activities required for monitoring, such as travel to site, sampling, analysis and simulation are excluded for accounting towards operational emissions in order not to discourage the use of robust monitoring protocols.

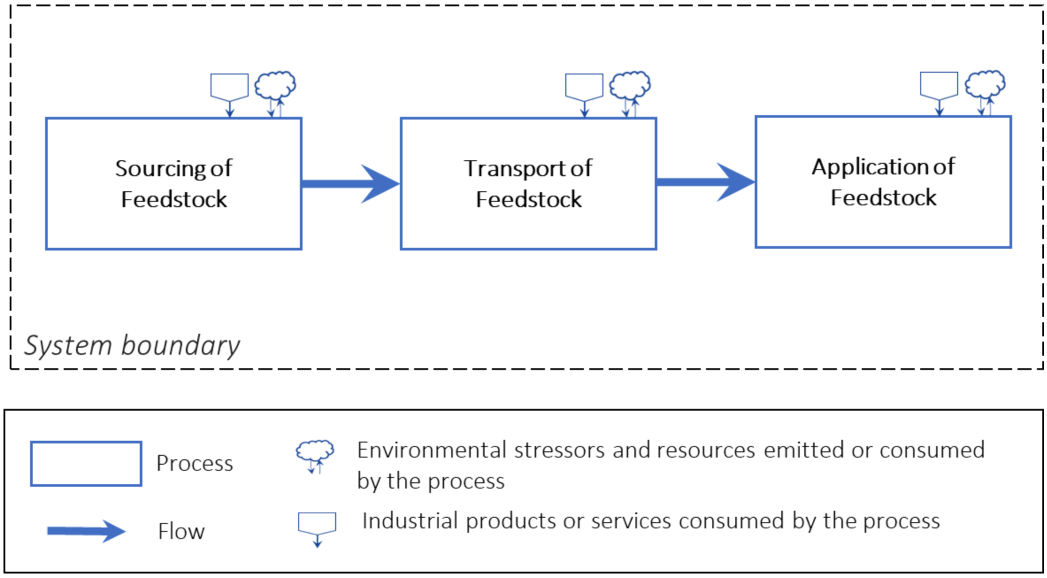

Figure 7.1. Generic process boundaries for ERW in soils.[43]

7.2.3. The **spatial dimension** of the ERW activity system shall be provided in a map or a geospatial vector data (shapefile) with the Project Description for the Production Facility Audit, and shall be defined in the LCA Model Description for the selection of spatially-relevant emission factors and activity data (see section 10.4). This includes the areas covered by the three unit processes, from feedstock sourcing to feedstock application. These may include the following:

a. **Mine location**: the origin of the rock or waste must be specified.

b. **Processing facility**: the site(s) of processing of the material must be specified.

c. **Application sites**: the area and the geolocation of the field site as well as the associated catchment in which the stored carbon is likely to be transported and stored (soil, groundwater, aquifer, watershed, rivers, ocean entry point), shall be specified

---

[43] Note that i) each process can be detailed in sub-processes, ii) additional transportation may be included in each process, iii) additional processes can be added as fit to the specific project.

7.2.4. The **temporal dimension** of the ERW activity system shall be defined in the LCA Model and LCA Model Description considering the GHG emissions accounting considerations of a crediting period and the fact that operational emissions (section 7.3) and embodied emissions (section 7.4) have taken place before the weathering of the weathering material and shall be accounted as follows:

- Operational emissions are associated with the deployment period (DP) following a weathering material application event, and shall be amortized across the "m" number of monitoring periods (MP) within its corresponding deployment period;
- Embodied emissions are associated with the whole ERW activity and shall be amortized as required in rule 7.4.5.

Note: During a crediting period, feedstock may be applied several times. Each application of weathering material marks the start of a new deployment period that lasts until a new weathering material application event or the end of the crediting period. Moreover, a deployment period may be subdivided into multiple monitoring periods for the purpose of carbon removal accounting and CORC issuance. Figure 7.2 provides an illustration of the relationship between crediting period, deployment period, and monitoring period.

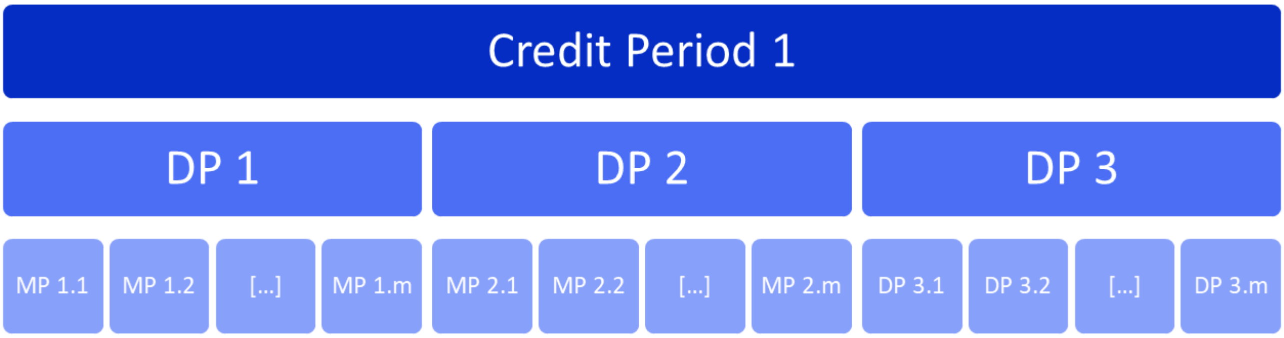

Figure 7.2. Example of the temporal dimensions of an ERW activity. DP: deployment period. MP: monitoring period.

7.2.5. The LCI included with the LCA model shall be provided in a disaggregated manner and aligned with table 7.1, exhibiting the contributions to each unit process (level 1) by the corresponding substage (level 2) and their contributors (level 3).

7.2.6. 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 unit process	Sub-stages Level 2 contributions	Further sub-stages Level 3 contributions	Comment
$E_{sourcing}$	*Operational emissions of feedstock production, supply, processing, (if applicable) and transport to the production site	Production Processing Supply	Third-level contributions may be split in sub-stages as relevant for each supply-chain.
	*Embodied emissions of feedstock extraction and processing assets	Construction and disposal of infrastructure and equipment *Direct land use change (dLUC)	Those emissions are verified at the Facility Audit, and then amortized evenly over the first crediting period.
$E_{transport}$	*Operational emissions of transporting feedstock	Energy use (heat, electricity, fuel) Material use Transport Waste treatment Stack emissions	Third-level contributions may be split in sub-stages as relevant for each supply-chain.
$E_{application}$	*Operational emissions for spreading the feedstock on site, excluding transportation from sourcing to site of use.	Energy use (heat, electricity, fuel) Material use Waste treatment	Third-level contributions may be split in sub-stages as relevant for each supply-chain.

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

7.3. Quantification of operational emissions

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 7.2.1, and calculate the **operational emissions** associated with the energy used to operate facilities, machinery, or other types of equipment as well as the material inputs (e.g., water, chemicals, packaging), waste treatment, and transportation (e.g., weathering material transportation) necessary for the carbon removal activity.

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

$$E_{ops,DP} = E_{sourcing} + E_{transport} + E_{application} \tag{7.2}$$

Variable	Description	Unit
$E_{ops,\,DP}$	Lifecycle operational emissions from materials and energy used for the application of a weathering material event and associated with a deployment period "DP".	tCO_2e
$E_{sourcing}$	Operational lifecycle emissions associated with sourcing of weathering material and its processing for its application.	tCO_2e
$E_{transport}$	Operational lifecycle emissions associated with transport of weathering material from the sourcing site to the application site.	tCO_2e
$E_{application}$	Operational lifecycle emissions associated with the application of weathering material to the application site.	tCO_2e

7.3.3. **Operational emissions shall be reported** evenly over a period of time in line with its corresponding monitoring period (see rule 7.2.4), or the lifetime assumption of the Production Facility, whichever is shorter. To calculate the amount of embodied emissions to amortize per monitoring period use eq. 7.3 as follows:

$$E_{ops,MP} = \frac{E_{ops,DP}}{m} \tag{7.3}$$

Variable	Description	Unit
$E_{ops,\,MP}$	Lifecycle operational emissions from materials and energy used by the project during the monitoring period.	tCO_2e
$E_{ops,DP}$	Lifecycle operational emissions from materials and energy used for the application of a feedstock event and associated with a deployment period "DP".	tCO_2e
m	Number of monitoring periods between application of feedstock on the site. "m" shall be equal or less than the number of monitoring periods defined under the monitoring period following an application event but preceding a subsequent application event or the end of the crediting period.	Unitless

- Alternatively, the CO_2 Removal Supplier may decide to amortize all embodied emissions earlier, for example, during the first monitoring period, if requested by a third party (e.g., investor or buyer).
- 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 in equal amount to the outstanding amount of emissions on one (1) tCO_2e to one (1) credit unit equivalence.

7.4. Quantification of embodied emissions

7.4.1. The CO_2 Removal Supplier shall calculate the **embodied emissions (E_{emb})** of the project for project validation, and submit for audit:

- A life cycle inventory of embodied emissions, accounting for the emissions of the foreground infrastructure and equipment, that includes the carbon emitted in the fabrication, construction, and demolition of infrastructure and/or equipment assets (E_{infra}), and in direct land-use conversion (E_{dLUC}) associated with the production facility and supporting infrastructure, when applicable (rule 7.4.2 to 7.4.4).
- Schedule of amortization of embodied emissions ($E_{emb,MP}$) to be included with the project emissions calculation (eq. 7.1) during the corresponding monitoring period based on the amortization rule 7.4.5.

7.4.2. The life cycle inventory of embodied emissions shall be estimated using eq. 7.4:

$$E_{emb} = E_{infra} + E_{dLUC} \tag{7.4}$$

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[44], EN 15978[45], or ISO 21930:2017[46].

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

---

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

[45] EN 15978:2012 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method.

[46] ISO 21930:2017 Sustainability in buildings and civil engineering works - Core rules for environmental product declarations of construction products and services.

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 operational pre-existing facilities shall not be accounted for in the project's embodied emissions. However, additional embodied emissions associated with the retrofit of the facility shall be accounted for.

d. In the event of an ownership change of an asset (e.g., trucks or agricultural machinery), the embodied emissions from the initial manufacturing shall be accounted to the pro-rata of its remaining lifetime. However, additional embodied emissions associated with the transportation, installation, or upgrading of the asset shall be accounted for in full.

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 or any supporting infrastructure necessary for the operation of the carbon removal activity. To this end, the following rules shall apply:

a. dLUC emissions shall be considered and included in the embodied LCI 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 built 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[47] (Tier 1), or country-specific values (Tier 2), or data specific to the project (Tier 3).

e. The calculation shall be performed using the eqs. 7.5 and 7.6 below:

$$E_{dLUC} = 44/12 \, * \, (CS_B - CS_P) \, * A + \, E_{conversion} \tag{7.5}$$

where the carbon stock per unit area is defined as:

$$CS_X = \, C_{VEG_X} \, + \, C_{DOM_X} + SOC_X \tag{7.6}$$

---

[47] 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds).

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.	$tC\ ha^{-1}$

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[48] 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[49] (see also subrule d).

7.4.5. **Embodied emissions shall be amortized**[50] evenly over a period of time in line with its first crediting period (10 years, see rule 2.2.6), or the lifetime assumption of the Production Facility, whichever is shorter. To calculate the amount of embodied emissions to amortize per monitoring period use eq. 7.7 as follows:

$$E_{emb,MP} = \frac{E_{emb}}{n} \tag{7.7}$$

Variable	Description	Unit

---

[48] 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds).

[49] 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).

[50] 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).

$E_{emb,MP}$	Amortized lifecycle embodied emissions associated with the production, use, and disposal of infrastructure and equipment assets and direct land use changes.	tCO_2e
E_{emb}	Sum of lifecycle emissions associated with infrastructure and equipment assets and direct land use changes.	tCO_2e
n	Number of monitoring periods under which the embodied emissions inventory will be amortized. “n” shall be equal or less than the number of monitoring periods defined under the crediting period.	Unitless

- Alternatively, the CO_2 Removal Supplier may decide to amortize all embodied emissions earlier, for example, during the first monitoring period, if requested by a third party (e.g., investor or buyer).
- 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 in equal amount to the outstanding amount of emissions on one (1) tCO_2e to one (1) credit unit equivalence.

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 feedstock deployment equipment and storage 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. Reporting of project emissions

7.5.1. The CO_2 Removal Supplier shall report project emissions every monitoring period by updating the LCA model with the corresponding operational and embodied emissions assigned to that period for accounting purposes.

7.5.2. The CO_2 Removal Supplier shall submit for Production Facility Validation the LCA model and a CORC summary calculation using expected values for a monitoring period, clearly defining the assumptions that will govern the project during the crediting period. The LCA results and the calculation of other contributing elements to the CORC calculation are ex-ante values that shall not be used to issue CORCs, but may be used to check that the project is performing within expected limits in future Output Audits.

Disaggregated results for auditing

7.5.3. The CO_2 Removal Supplier shall submit LCA results in the LCA model and CORC calculation summary 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, ensuring the transparency and interpretability of the results and facilitating the auditing process (i.e., verification of claims).

Aggregated results for public disclosure

7.5.4. 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.

8. Determination of Leakage ($E_{leakage}$)

The concept of leakage in the Puro Standard General Rules refers to the increase or decrease of greenhouse gas (GHG) emissions generated by the carbon removal activity outside of its system boundary and the activity's baseline scenario. For the purpose of CORC quantification, only the increase in GHG emissions or decreases in carbon stocks are quantified, and subtracted to arrive at the activity's net carbon removal if not avoided or mitigated. Net positive effects are not included in the quantification of CORCs.

As defined in the Puro Standard General Rules, the scoping for sources of leakage is performed at the methodology level and shall result in a list of such sources. Further, Puro categorizes sources of indirect effects in two groups, whose definition is reminded here:

- **Ecological leakage**: a project can change the greenhouse gas fluxes mediated by ecosystem-level changes in surrounding areas outside of the project boundaries, specially with hydrologically connected land areas. This is also referred to as potential negative effects to nearby land and ecosystem.
- **Market and activity shifting leakage**: a project can generate competition for resources and services, altering the supply-demand equilibrium, leading to changes in price and availability of goods or services, causing an increase/decrease in emitting activities elsewhere (market effects) and a project can displace an activity or change the likelihood of an activity outside the project's boundaries (activity shifting). These two notions are grouped together as they are often interrelated and sometimes necessary to assess jointly.

This section defines the relevant sources of leakage emissions that could be associated with the ERW carbon removal activity, following the three-step approach defined in the Puro Standard General Rules:

1. Determine potential leakage source (see section 8.1).
2. Avoid or mitigate leakage sources (see section 8.2).
3. Quantify unmitigated leakage (see section 8.3).

8.1. Identification and characterization of leakage emissions

The availability of basalt and other rocks suitable for ERW may be limited due to geological factors. Moreover, there is strong commercial demand in well-established markets for construction aggregate, metal extraction, glass/ceramics manufacturing, and decorative stone. As a consequence, this methodology anticipates that an ERW activity may lead to a competing use of natural rocks for carbon sequestration, and could include as a potential source of leakage the indirect land use change impact associated with mining operations to meet the demand for the product.

8.1.1. The CO_2 Removal Supplier shall disclose the location from which the rock is sourced from and provide market reports of current market supply and expected demand growth to determine whether the ERW activity will increase the demand for rock.

Note: If the CO_2 Removal Supplier cannot determine or provide evidence of feedstock sourcing, it is conservatively assumed that there is a competing market demand for the material and leakage shall be quantified according to rule 8.3.1.

8.2. Mitigation of leakage emissions

8.2.1. The CO_2 Removal Supplier shall demonstrate for each deployment period (see rule 7.2.4) that the demand for feedstock rock by the ERW activity does not exceed the current local market available supply to consider that leakage is avoided. However, when feedstock is imported from outside the country where the ERW activity is taking place, it is conservatively assumed that leakage is taking place, and shall be quantified using rule 8.3.1.

8.3. Quantification of non-mitigated leakage emissions

8.3.1. The CO_2 Removal Supplier shall estimate the impact on carbon stocks associated with forest areas being converted into barren lands as a proxy for the expansion of mining operations. This quantification is driven by demand of rock used by the project during each monitoring period (see rule 7.2.4) and shall be accounted for in connection with the IPCC guidelines for land use change as follows:

a. These emissions shall be quantified using either the default values for land conversion available in the IPCC Guidelines for National Greenhouse Gas Inventories[51] (Tier 1), or country-specific values (Tier 2), or data specific to the project (Tier 3).

b. The estimation of land use change area (A) uses a quarry yield of 5000 t/ha/year and estimates an additional 30% of ancillary land use change to facilitate access and operations of the quarry, using the following formula:

$$A_{converted} = 1.3 \times Q_{yield} \times Q_{rock} \tag{8.1}$$

Variable	Description	Unit
$A_{\text{converted}}$	Area of land converted.	ha
1.3	Ancillary land use factor	unitless
Q_{yield}	Estimated quarry yield per unit area.	$t\ ha^{-1}\ year^{-1}$
Q_{rock}	Amount of rock applied to site	tonne

c. The calculation shall be performed using eqs. 8.2 and 8.3:

---

[51] 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds).

$$E_{leakage} = 44/12 \times (CS_B - CS_P) \times A_{converted} + E_{conversion} \tag{8.2}$$

where the carbon stock per unit area is defined as:

$$CS_X = C_{VEG_X} + C_{DOM_X} + SOC_X \tag{8.3}$$

Variable	Description	Unit
$E_{leakage}$	Absolute direct land use change associated with the new mining operations.	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.	$tC\ ha^{-1}$
$A_{\text{converted}}$	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.	$tC\ ha^{-1}$

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[52] 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[53] (see also rule 7.4.4 d).

---

[52] 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds).

[53] 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).

9. Monitoring Requirements

9.1. General principles

Monitoring, measuring, and reporting the performance of the carbon removal activity is essential to ensure that the requirements prescribed in this methodology have been fulfilled. Due to the complexity of the underlying system and the lack of consensus on quantification approaches (see section 11.2), it is paramount that the monitoring plan is designed in a robust manner, based on up-to-date scientific knowledge and substantial baseline measurements in the local system.

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 conducted 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 Enhanced Rock Weathering 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 CO_2 is sequestered and effectively stored long-term, that soil, groundwater, and the environment more generally 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 and abide by a **Monitoring Plan** to assess the performance of the carbon removal activity.

a. The Monitoring Plan shall be developed in conjunction with the Quality Control Procedures (section 10.3) and describe the procedures by which the CO_2

Removal Supplier will collect data and evidence in accordance with ISO 14064-2:2019[54] and Puro Standard requirements.[55]

b. The scope of the Monitoring Plan shall cover all aspects related to:

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

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

   iii. measuring the project's carbon sequestration (C_{stored}, $C_{baseline}$, C_{loss}) and GHG emissions (section 5, section 6, section 7, and section 8); and

   iv. monitoring the risk of reversals (section 9.6).

c. The suite of monitoring technologies described in the Monitoring Plan shall be:

   i. chosen such as to enable the verification of the changes in carbon stock based on the different quantification approaches included in this methodology (section 11.2), in support of the sampling approach (section 11.1), and following the QC procedures (section 10.3); and

   ii. adapted to the site-specific needs of the Removal Activity.

9.2.2. The Monitoring Plan shall include the following components:

a. description of the monitoring practices based on their purpose;

b. project boundaries and monitoring system diagram;

c. roles and responsibilities of the project personnel involved in the monitoring and data collection processes;

d. data collection plan for feedstock characterization, CORC quantification, and pre-application soil characterization, including at least:

   i. a list of all utilized parameters and their associated attributes in accordance with table 9.1; and

   ii. sampling strategy (including criteria for definition of homogeneous strata (rule 11.1.1), use of evaluation area, assignment of control sites (rule 11.1.4).

e. LCA model and description, including:

   i. separate LCI for operational and embodied GHG emissions; and

   ii. clearly stating which activity data (AD) to collect and which uses average or fixed values;

---

[54] 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.

[55] Available in the Puro Standard document library.

f. uncertainty assessment and quantification procedures;

g. description of data quality control (QC) procedures (see section 10.3);

h. description of the information management system for record keeping and data management;

i. definition of expected or normal values or value ranges, or threshold values;

j. procedures to define and respond to significant irregularities in the project performance (i.e., contingency monitoring), including the case of reversal events, and violation of environmental and social safeguards; and

k. information about any internal or external laboratories, and outsourced procedures utilized (names and addresses), and their relevant accreditation, if applicable (see also rule 10.3.4).

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[56], and is required to be made available in the Public Registry, either in full or in a redacted form for confidentiality, once the Facility Audit is successfully completed.

9.2.4. The Monitoring Plan shall be periodically evaluated and updated to ensure the monitoring practices remain appropriate and effective.

a. The evaluation shall include a reassessment of the site-specific monitoring requirements and risks.

b. Updates to the monitoring plan might be necessary due to:

   i. changes to the Production Facility that affect the activities being monitored;

   ii. changes to the Puro normative framework that require an update in the monitoring activities; and

   iii. corrective actions requested from the auditor.

c. All changes to the Monitoring Plan are subject to re-validation by the third-party auditor during the next available Output Audit.

9.2.5. The CO_2 Removal Supplier shall utilize the parameters and monitoring procedures described in the Monitoring Plan to report and provide evidence of the Production Facility performance for each monitoring period in accordance with the reporting requirements described in section 13.

---

[56] Available in the Puro Standard document library.

Table 9.1. Information to be compiled in the monitoring plan for each relevant parameter involved in the LCA and CORC calculations, and environmental and social safeguards (see rule 9.2.2.d.i).

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	A brief text describing where the data is sourced from: measured (m), calculated (c), or estimated (e).
Monitoring frequency	The frequency of monitoring of the parameter.
Monitoring density	The density (in number of samples per area of field site) 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 in light of possible error or uncertainty.
Measurement uncertainty (%)	An estimation of the ***random error*** component associated with the measurement, and estimated as percentage uncertainty in the parameter.
Comments	Free text comments

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.[57]

a. In the case where any deviations or non-conformities with the eligibility requirements or validated Production Facility design are detected during a monitoring period, the CO_2 Removal Supplier shall without delay:

   i. notify the Issuing Body;

   ii. develop a plan to solve the situation at the earliest possible; and

   iii. demonstrate actions to meet the eligibility requirements.

b. The non-conformity with the eligibility requirements can:

---

[57] Available in the Puro Standard document library.

i. impact the verification of the Output of the Production Facility and the corresponding CORC issuance for that period; and/or

ii. require the Issuing Body to suspend the Production Facility in accordance with the Puro Standard General Rules.[58]

9.3.2. The CO_2 Removal Supplier shall keep a record of the documentation that supports the chain of custody of the eligible sources of weathering feedstock in accordance with requirements for sustainability and traceability of origin (see section 3.8) and make that documentation available for third-party verification upon request.

9.4. Characterization of the field site prior to feedstock application

9.4.1. The CO_2 Removal Supplier shall comprehensively characterize the field site by sampling prior to spreading weathering material in order to:

a. Evaluate site eligibility (see section 3.9).

b. Establish the environmental conditions of the storage site prior to weathering material deployment and assess environmental changes due to the ERW activity (rule 9.4.4).

c. Determine homogeneous strata for sampling strategy (section 11.1)

9.4.2. **Subsequent monitoring periods**: From the second monitoring period at a given field site onwards, measurements taken at the end (t_1) of the preceding monitoring period may be used as part of the pre-application soil characterization for the new monitoring period, unless the preceding monitoring period ended more than 1 year before the start of the new monitoring period.

9.4.3. Data from the pre-application soil characterization measurements may be re-used to (partially) replace t_0 measurements in cases where t_0 is measured before feedstock application as long as the samples underlying these data were taken within 12 months of the beginning of the monitoring period (i.e., the date at which the feedstock was spread) and no relevant changes were made to the soil by natural events (e.g., floods, exceptional weather events) or anthropogenic actions (e.g., agronomic practices outside the usual pattern such as different fertilizer application schemes) that could reset the baseline.

9.4.4. The CO_2 Removal Supplier shall conduct soil analyses at the field site before spreading of the weathering material (i.e., before the start of a Deployment Period, see rule 7.2.4, figure 7.2) as well as at some point between spreading and end of the Deployment Period as further specified in subrules a-e and listed in table 9.2. This is for the purpose of monitoring the influence of the ERW activity on soil ecological health and to inform efficient ERW deployment, including the identification of homogeneous strata (see rule 11.1.1, rule 11.1.2).

---

[58] Ibid.

a. The soil analysis shall determine the soil type(s) and initial (pre-application) physical and chemical characteristics of the field site by applying the measurements listed in table 9.2. Some of these measurements shall be repeated after feedstock application on application and control sites as specified in table 9.2.

b. Sampling depth (if applicable) for soil characterization purposes shall equal the sampling depth applied for C_{stored} on a given field site and follow the same rules (11.2.9-11.2.11).

c. In order to determine the information required in subrule a, the CO_2 Removal Supplier may, where available, utilize representative external sources of information, such as values from soil databases or previous measurements (e.g. measurements conducted as part of typical agronomic practices of the region). However, the CO_2 Removal Supplier *should prefer* direct measurements and utilize external sources of information to complement, rather than to replace, experimental baseline sampling.

d. The CO_2 Removal Supplier shall ensure that the collected soil information before feedstock spreading is statistically representative of the entire field site by employing appropriate sampling strategies (e.g., split field, randomized control, grid sampling) as well as a sampling density appropriate to the site-specific characteristics of the field site (such as the types of soils within the Production Facility and the underlying spatial variability thereof, typical parameter ranges and variance). The minimum sampling density guidelines in table 11.1 may serve as initial guidance but more sampling is recommended where initial results suggest higher variability in relevant parameters (see table 9.2).

e. The sampling density of relevant parameters for soil condition monitoring after feedstock application (see table 9.2) can likely be lower than before feedstock application, because conditions are by that point understood better. Therefore, to assess changes in soil condition due to feedstock application, post-feedstock application samples shall be taken at least from each homogeneous stratum (rule 11.1.1).

Table 9.2. Overview of required and recommended measurements with recommended analytical methods for pre-application soil characterization, including agricultural parameters. Note that requirements and recommendations or lack thereof refer only to soil characterization and not to C_{stored} or C_{loss} quantification for which separate requirements apply.

Parameter	Analytical methods and reference	Before feedstock application	After feedstock application (application sites)	After feedstock application (control sites)
Soil type/texture (including clay, sand, silt percentages)	(IUSS Working Group WRB, 2022); USDA Soil Taxonomy (USDA Natural Resources Conservation Service. Keys to Soil Taxonomy, 13th Edition. Washington, D.C.: United States Department of Agriculture, 2022); (C. Ditzler, 2023)	Required	Not required	Not required
SOC	Dry combustion (ISO 10694:1995)	Required (rule 4.5.1)	Required (rule 4.5.1)	Required (rule 4.5.1)
SIC	Thermogravimetric analysis (TGA), calcimetry (ISO 10693:1995), dry combustion ((Leogrande et al., 2021), ISO 10694:1995)	Required	Required	Required
Bulk soil major cations, including Mg, Ca, K, Na.	ICP-MS or ICP-OES (e.g., ISO 22036:2024) after soil digestion (e.g., ISO 14869-3:2017, Mehlich-3 (Mehlich, 1984))	Required	Not required	Not required
Soil bulk density	ISO 11272:2017	Required	Not required	Not required
Soil pH	ISO 10390:2021	Required	Required	Required
CEC	ISO 11260:2018, ISO 23470:2018,NH_4OAc extraction at pH7 (in Kellogg Soil Survey Laboratory Methods Manual No. 42, v 6.0, part 1) or similar as appropriate for local soil pH.	Required	Required	Required
Heavy metals (listed in table 4.3, see also section 4.5.	ICP-MS (ISO 17294-1:2024) or ICP-OES (ISO 11885:2007) after acid digestion (EPA 3050B)	Required (see rule 4.5.4 and rule 3.9.3)	Required (rule 4.5.4)	Required (rule 4.5.4)
Crop type	Agricultural documentation	Required	Required	Required
Agricultural yield or year-over-year yield difference	Agricultural documentation	Required (if farmer consents to sharing yield data[59])	Required (if farmer consents to sharing yield data)	Required (if farmer consents to sharing yield data)

---

[59] Note that stakeholders have the option of using feedback and grievance mechanisms outlined in the Puro Stakeholder Engagement Requirements, section 2.5.

Parameter	Analytical methods and reference	Before feedstock application	After feedstock application (application sites)	After feedstock application (control sites)
Plant cation composition	EPA Method 3050B, AOAC Official Method 975.03, ICP-MS (ISO 17294-1:2024), ICP-OES (ISO 11885:2007)	Recommended	Recommended	Recommended
Organic and inorganic fertilizer application	Agricultural documentation	Recommended	Recommended	Recommended

9.5. Monitoring for C_{stored} quantification

Evidence requirements for C_{stored}

9.5.1. The CO_2 Removal Supplier shall quantify the gross amount of carbon stored during the monitoring period (C_{stored}) utilizing site-specific empirical measurements in accordance with the quantification approaches described in section 11.2.

9.5.2. The CO_2 Removal Supplier shall quantify the gross amount of carbon stored (C_{stored}) (equation 5.1) based on data from two different measurement approaches (i.e. the *quantification approach* and *verification approach*), as further detailed in subrules a-c.

a. The CO_2 removal supplier shall select the quantification approach and the validation approach in accordance with the following restrictions.

    i. The quantification and validation approaches shall be selected amongst the measurement approaches described in section 11.2 and listed in table 6.1.

    ii. The quantification and validation approaches shall be of different types, i.e. they shall neither both be soil-based approaches (A1 and A2) nor shall they both be water-based approaches (A3-A5; see table 6.1).

    iii. Approach A5 (CAT_{resin}) shall not be utilized as the quantification approach, and may only be utilized as the validation approach.

    iv. Approach A6 (SIC_{soil}) shall not be utilized as either the quantification approach or the validation approach. Rather, it is an optional approach that may be used independently of the other approaches to quantify additional C_{stored} in the form of secondary carbonates (see rule 11.3.7).

b. To validate the value for C_{stored}, at, the CO_2 Removal Supplier shall adhere to the following procedure:

    i. The CO_2 Removal Supplier shall randomly select at least 50% of the homogeneous strata to be monitored with the validation approach as well as the quantification approach (the remaining strata may be monitored with the quantification approach only). The strata thus selected are called the validation set.

ii. For each stratum in the validation set, the CO_2 Removal Supplier shall derive values for C_{stored} *in that stratum* using both approaches (i.e. a pair of values, termed $C_{stored,\ validation}$ and $C_{stored,\ quantification}$, for each stratum in the validation set).

iii. The validation is considered passed if, for each stratum in the validation set, the value for $C_{stored,\ validation}$ is within three standard deviations of the value of $C_{stored,\ quantification}$ for that stratum. Otherwise, the validation is considered failed.

iv. If the validation is passed, the final value for C_{stored} (i.e. the total aggregated value across all strata) shall be the value obtained using the quantification method.

v. If the validation fails, the CO_2 Removal Supplier shall provide explanation and justification for the discrepancy, which shall be subjected to the examination of the Issuing Body for potential approval as is or additional validation requirements.

c. The sampling requirements in section 11.2 (including but not limited to the minimum sampling density in table 11.2) apply separately to both the quantification and the validation method.

9.5.3. Additional evidence for the accuracy of C_{stored} shall be provided by estimating CDR_{max}. The estimation shall be based on measurement of the major cation concentration in the weathering feedstock, e.g., by full acid digestion followed by either XRF or ICP-OES analysis (table 3.1). Additionally, the carbon content of the feedstock (estimated either by dry combustion of loss-on-ignition, see table 3.1) shall be taken into account to correct for the share of positive (cation) charges balanced by carbonate (e.g., estimate the share of CaO representing calcium carbonate). The results from these analyses shall be combined with the amount of feedstock applied per area of application site (rule 3.7.3c) to calculate CDR_{max} (eq. 1.6) which shall be considered the maximum CDR capacity of the feedstock given its composition and applied volume. In cases where $C_{stored} \geq CDR_{max}$, the value of C_{stored} shall be considered invalid and the CO_2 Removal Supplier shall trace the error that led to this evident overestimation of C_{stored} and, if appropriate, recalculate C_{stored} before CORCs can be issued.

9.6. Monitoring for CO_2 release and reversal

9.6.1. 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.[60] Note, that only previously unknown or unanticipated re-emissions *after issuance of CORCs* are termed

---

[60] Available in the Puro Standard document library.

reversals, and separated from carbon losses which are accounted for *at the time of CORC issuance* (see section 6.3).

9.7. Monitoring for environmental and social impacts

9.7.1. 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.[61] 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.

9.7.2. 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.[62]

b. The social risks identified in the Puro Stakeholder Engagement Report[63], 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.[64]

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.[65]

9.7.3. The CO_2 Removal Supplier shall monitor the environmental impacts (changes to the initial conditions) using measurement procedures described in section 10.

9.7.4. The CO_2 Removal Supplier shall design and implement an "Ongoing feedback and grievance mechanism" as described under the Puro Stakeholder Engagement Requirements[66] 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.

---

[61] Ibid.

[62] Available in the Puro Templates and Guidelines library.

[63] Ibid.

[64] Ibid.

[65] Ibid.

[66] Ibid.

9.7.5. 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.

9.7.6. The CO_2 Removal Supplier shall address any grievances in accordance with the mitigation hierarchy described in section 4.2.

9.8. Monitoring for greenhouse gas accounting

9.8.1. The CO_2 Removal Supplier shall collect monitoring data from all project activities to measure and calculate GHG emissions and carbon removals in order to determine the net carbon removal in accordance with the CORC equation (figure 5.1). All collected data relevant to CORC issuance must be reported, specifically negative (i.e., lack of CDR) data shall not be excluded.

9.8.2. The CO_2 Removal Supplier shall follow the requirements described in section 9 and section 13 when preparing the monitoring plan.

10. Uncertainty Quantification and Discounting

10.1. General principles

Puro Standard Methodologies strive to minimize, quantify, and manage the uncertainties associated with conceptualisation and modelling the carbon removal activity. In general, uncertainty in quantification results from *observational errors*, which refer to the difference between an observed or measured value of a quantity and its unknown 'true value'. In the context of uncertainty assessment, these differences are further characterized by the concepts of *accuracy* and *precision* (see figure 10.1):

- Accuracy refers to how closely the average of repeated measurements or predictions corresponds to the true value of a variable. Accuracy implies the absence of *systematic error*, and translates for example into the need for proper calibration of measuring equipment and the use of representative data.
- Precision refers to the degree to which repeated measurements of the same variable produce consistent results. A higher precision indicates lower *random error*, obtained, for example, through the use of more precise measurement devices or the gathering of more data points.

For the purposes of this methodology, the uncertainties themselves can be also divided into two broad broad classes based on the source and nature of the uncertainties:

- Random errors refer to errors caused by unknown and unpredictable changes in the system or the experiment affecting the *precision* of quantification (see figure 10.1). These errors are not repeatable, and are uncorrelated between measurements. Random errors can arise from factors such as the inherent variability of environmental conditions (e.g. fine-scale soil heterogeneity), or incidental measurement errors (e.g., due to precision of the measurement device itself, or unpredictable variations in sample preparation). While random errors are unpredictable and always present, they can be estimated by statistical methods (see section 10.5).
- Systematic errors (or bias) refer to errors associated with repeatable processes inherent to the system affecting the *accuracy* of quantification (see figure 10.1). These errors often either remain constant or change in a predictable manner with changing conditions. Systematic errors can arise from innumerable sources, such as:
    - ○ a flawed characterization of the study variables or their sampling and measurement procedures (e.g. flawed experiment design, faulty or miscalibrated equipment); or
    - ○ an incomplete understanding or other conceptual inaccuracies in the processes included in measurement and quantification (e.g. inaccurate or oversimplified assumptions underlying the quantification approach).

  Systematic errors can, to a certain extent, be eliminated via reviewing, criticizing, and modifying the quantification approach and measurement procedures. However, deep conceptual inaccuracies (so-called "unknown unknowns")—resulting, for example, from incomplete scientific understanding of the weathering process itself—can be difficult or impossible to completely eliminate.

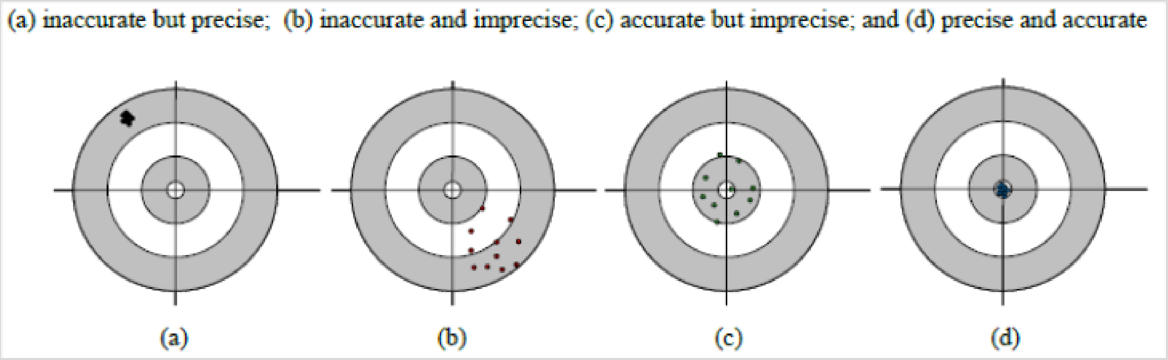

Figure 10.1. Illustration of accuracy and precision (Buendia et al., 2019). Note that precision is independent of accuracy, meaning that measurements can be precise without necessarily being accurate.

For robust results, it is important to reduce quantification uncertainties as much as possible, and the CO_2 Removal Supplier plays an important role in minimizing the uncertainty associated with the carbon removal activity performance (see also section 10.2 and 10.5). For example, the quantification of the gross amount of carbon removed (i.e. the C_{stored} component of the CORC equation, see section 6.1) can be affected by significant sources of uncertainty. For example, this component includes systematic errors linked to the understanding of the weathering processes, and challenges in monitoring and measuring chemical changes in the soil over time. The quantification is furthermore influenced by random errors due to both the inherent variability of soil conditions as well as factors such as measurement or sampling errors.

The estimation and management of errors, as well as uncertainty assessment in general have been extensively studied, and further relevant information on the treatment uncertainty can be found, for example, in the IPCC Guidelines for National Greenhouse Gas Inventories[67] (Buendia et al., 2019; Eggleston et al., 2006). In this methodology, the requirements for uncertainty estimation and management include, for example, the assessment of potential causes for uncertainties and mitigation strategies (see section 10.2), quality control procedures (section 10.3), and quantification and discounting of uncertainty (section 10.5).

10.2. Uncertainty assessment

10.2.1. The CO_2 Removal Supplier shall undertake an uncertainty assessment of the implementation of the ERW activity, as further detailed in subrules a-c.

a. The purpose of the uncertainty assessment is to:

   i. Identify and quantify the possible causes of uncertainty (see subrule b).

---

[67] See in particular IPCC Guidelines for National Greenhouse Gas Inventories, Volume 1: General Guidance and Reporting, Chapter 3: Uncertainties and Reporting, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, and 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

   ii. Establish actions that reduce uncertainty through the design of the ERW activity, and improve the accuracy and precision of the net carbon removal calculation (see subrule c).

b. The uncertainty assessment shall address the potential causes of uncertainty summarised in table 10.1.[68]

c. The uncertainty assessment shall at least encompass:

   i. Specification of the parameters that contribute to the quantification model described by the overall CORC equation (see figure 5.1).

   ii. Quantification of uncertainty estimates for the parameters used for the quantification of the net carbon removal process (see 10.5.2).

   iii. Calculating the overall uncertainty of the net CO_2 removal activity based on the mathematical combination of uncertainties (utilizing, e.g., frequentist or Bayesian methods, see section 10.5).

d. The uncertainty assessment shall define the actions to be taken by the CO_2 Removal Supplier to reduce the causes of uncertainty in the implementation of the Enhanced Rock Weathering activity in accordance with the quality control procedures for each parameter included in data collection (section 10.3).

Table 10.1. Causes of Uncertainty (after Buendia et al., 2019; Eggleston et al., 2006)

Cause of uncertainty	Type	Potential mitigation actions
Lack of data	Bias	Quality Control: expert judgement
Lack of representativeness of data	Bias	Quality Control: Pedigree matrix approach[69]
	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

---

[68] The CO_2 Removal Supplier should refer to the IPCC Guidelines for National Greenhouse Gas Inventories and General Guidance and Reporting for further information on treating uncertainty (Buendia et al., 2019; Eggleston et al., 2006). Note that the IPCC Guidelines include two additional causes of uncertainty excluded from table 10.1. These are the lack of completeness in the system definition and the model formulation. Both causes are addressed in this methodology through the selection of the quantification approaches.

[69] GHG Protocol Quantitative Uncertainty Guidance.

10.3. Quality control (QC) system and procedures

A quality control system and procedures are paramount to ensure the accuracy and reduce the uncertainty in the GHG emission calculations and other data required to assess the carbon removal activity's performance.

10.3.1. The CO_2 Removal Supplier shall ensure that all parameters required by this methodology—including but not limited to total net carbon removal, and environmental and social indicators (e.g. concentrations of potentially toxic elements)—are quantified *accurately* and *precisely* in accordance with this methodology as well as all applicable local laws, regulations, and other binding obligations.[70] This shall be evidenced by means of the quality control (QC) system (see rule 10.3.2) and data collection practices (see section 10.4 and table 10.2).

10.3.2. The CO_2 Removal Supplier shall have in place and abide by a quality control (QC) system as further detailed in subrules a-c.[71]

a. The quality control system is comprised of:
   i. quality control procedures to measure and control the quality of the GHG inventory for the calculation of the net carbon removal (see rule 10.3.3); and
   ii. data necessary for other monitoring purposes (see rule 9.2.1 b).

b. The purpose of the quality control system is to:
   i. ensure the data is presented in accordance with the principles of relevance, completeness, consistency, accuracy, transparency, and conservativeness as described in ISO 14064-2;[72]
   ii. identify and address errors and omissions; and
   iii. document and archive all inventory material and records in accordance with rule 13.1.5.

c. The CO_2 Removal Supplier shall prepare a quality control plan providing a detailed description of the quality control system and any updates thereof (see also rules 10.3.2 and 10.3.3).

10.3.3. The quality control (QC) procedures shall include at least the following components:

a. Roles and responsibilities:

---

[70] Note that accuracy and precision depend on the uncertainty associated with the processes and data inputs involved in quantification of the parameters (e.g. the GHG emissions, or the net carbon removal from the implementation of the ERW activity).

[71] The CO_2 Removal Supplier should consult the IPCC Guidelines for National Greenhouse Gas Inventories (2006, 2019) for more detail in the development of a QC system.

[72] 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.

    i. Identify the parties involved in coordinating the implementation of the quality control procedures.
    ii. Maintain a responsibility matrix to track ownership of data streams and quality tasks.

b. Documentation and data traceability:
    i. Ensure complete documentation of all data sources, assumptions, and emission factors, and version control for all data management tools.
    ii. Maintain an audit trail for data collection, processing, storage, and reporting.

c. Activity data verification:
    i. Perform independent checks of activity data (e.g., feedstock measurements, land-use data, energy/fuel inputs).
    ii. Cross-verify field data with source documentation (e.g., invoices, satellite imagery, sensor logs).

d. Emission factor validation:
    i. Confirm appropriateness and consistency of default or project-specific emission/removal factors, and reference their database sources or peer-reviewed studies.

e. Data Entry and Transcription Checks:
    i. Implement double data entry or automated error-checking procedures for manual entries.
    ii. Review calculations and database queries for coding or logic errors, when applicable.

f. Uncertainty analysis:
    i. Identify key data sources and quantify uncertainties as per rules in section 10.5.
    ii. When possible, require laboratory analyses to be conducted by laboratories accredited under ISO 17025 and request laboratory results with their corresponding uncertainty estimation.

g. Internal audits and peer reviews:
    i. Schedule regular internal QC reviews by qualified personnel not involved in data collection.

h. Data management and storage (record keeping):
    i. Ensure secure and redundant storage of all relevant data (field logs, photos, GIS files).

    - ii. Apply access controls to protect data integrity while ensuring appropriate transparency.
    - iii. Ensure confidentiality of the managed information, when required.
  - i. Calibration and maintenance of instruments:
    - i. Ensure all measurement instruments are installed, operated and regularly calibrated according to the device manufacturer’s specifications or according to an appropriate industry consensus standard.
    - ii. Maintain logs of instrument maintenance, calibrations, and replacements.
  - j. Training and competency assurance:
    - i. Provide training for field staff, data analysts, and QC reviewers on methods and quality procedures.
    - ii. Document qualifications and continuous improvement activities.
  - k. Reporting and corrective actions:
    - i. Establish a mechanism for reporting QC findings, inconsistencies, and corrective actions.
    - ii. Track resolution of issues and integrate lessons learned into QC plan and procedures.

10.3.4. The CO_2 Removal Supplier shall ensure that laboratories used to carry out analysis for the quantification of carbon removal and environmental impacts meet the requirements equivalent to EN ISO/IEC 17025, including the following:

  - a. Evidence of implementation of appropriate quality management procedures in the form of at least one of the following:
    - i. accredited certification of the laboratory in conformity with EN ISO/IEC 9001 or other certified quality management systems;
    - ii. other similar documentation and evidence of the utilized quality management procedures to the satisfaction of the Issuing Body.
  - b. Evidence of technical competence covering all of the following elements:
    - i. management of the personnel's competence for the specific tasks assigned;
    - ii. suitability of accommodation and environmental conditions;
    - iii. selection of analytical methods and relevant standards;
    - iv. where applicable, management of sampling and sample preparation, including control of sample integrity;
    - v. Use of replicate analysis, standardized reference material (e.g., of known analyte concentration), and blanks analyzed in parallel to actual samples in

order to determine the analytical precision, analytical accuracy, and analytical detection limit, respectively;

vi. where applicable, development and validation of new analytical methods or application of methods not covered by international or national standards;

vii. uncertainty estimation;

viii. management of equipment, including procedures for calibration, adjustment, maintenance and repair of equipment, and keeping records thereof;

ix. management and control of data, documents and software;

x. management of calibration items and reference materials;

xi. quality assurance for calibration and test results, including regular participation in proficiency testing schemes, applying analytical methods to certified reference materials, or inter-comparison with an accredited laboratory;

xii. management of outsourced processes; and

xiii. management of assignments, customer complaints, and ensuring timely corrective action.

10.3.5. The CO_2 Removal Supplier shall periodically review and update the QC procedures based on methodological advances or feedback and findings from the third-party validation of the QC plan and verification of the Output Report. Examples of such improvements include (but are not limited to) improving the estimates of emissions and/or removals, or reassessing data compilation processes and uncertainty estimates.[73]

10.4. Data Collection

10.4.1. The CO_2 Removal Supplier shall collect the necessary data in accordance with the Monitoring Plan to fulfil the requirements of this methodology as well as all other Puro Standard requirements[74], and requirements imposed by any applicable local laws, regulations, and other binding obligations.

10.4.2. The CO_2 Removal Supplier shall calculate the net carbon removal for each monitoring period. The calculation process and its result shall be included in the Output Report (see section 13) and made available to the Auditor for the Output Audit.

---

[73] In particular, the CO_2 Removal Supplier should strive to reduce the parameter uncertainty and improve the quantification of the inventory of GHG emissions and carbon removal based on the data and information obtained from quantification of uncertainty (see section 10.5).

[74] Available in the Puro Standard document library.

10.4.3. The CO_2 Removal Supplier shall define the attributes listed in table 10.2 for all parameters described in the Monitoring Plan.

Table 10.2. List of required parameter attributes.

Attribute	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.
Type of data	Classify the type of data as measured (m), estimated (e), or calculated (c) based on the definitions described in rule 10.4.4.
Source of data	Reference of the data source: database, peer-reviewed study, etc.
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 ***standard uncertainty*** (see section 10.5) associated with the measurement, where applicable.
Data archive process	A brief text describing how the data is archived.
Time of data archive	For how long will the data be archived?
Comments	Free text comments

10.4.4. The CO_2 Removal Supplier shall classify the parameters described in the Monitoring Plan as either measured (m), estimated (e), or calculated (c) as further defined in subrules a-c. In cases of ambiguity, the CO_2 Removal Supplier may utilize best judgement to select the closest match.

a. **Measured**: parameters, whose values are obtained directly from an instrument or observation. The measurements may be conducted by the CO_2 Removal Supplier, or by external operators (such as external laboratories), provided that the CO_2 Removal Suppliers has access to the measurement data and relevant metadata for analysis of the results and associated uncertainty.[75]

---

[75] Measurement uncertainty depends on factors such as precision and calibration of measuring instruments, the sampling design, handling, etc.

b. **Estimated**: parameters, whose values are inferred using judgment, approximation, or indirect evidence (often when direct measurement is not possible), including parameters, whose values are obtained from scientific peer-reviewed literature, national or locally available survey maps or databases (e.g. databases for emission factors and average activity data), or other similar robust sources of information.

c. **Calculated**: parameters, whose values are obtained by applying a defined mathematical relationship or model to measured or estimated inputs.

10.4.5. The CO_2 Removal Supplier shall report parameter values in the units of measurement specified in this methodology or any reporting templates, guidance documents or other supplementary materials provided by the Issuing Body. For parameters where no specific unit is explicitly required, the International System of Units (SI) are the preferred units of measurement, but the CO_2 Removal Supplier may utilize other unit measurement systems (e.g. the British imperial system and the United States customary system).

10.5. Quantification of measurement uncertainty

Knowledge of measurement uncertainty implies increased confidence in a result's validity (Ellison, S L R & Williams, 2012). In the context of this methodology, the main object of estimating measurement uncertainty is the net carbon dioxide removal based on the elements that contribute to the CORC calculation. The CO_2 Removal Supplier should refer to the ISO/IEC Guide 98 series or the EURACHEM-CITAC Guide CG 4 (Ellison, S L R & Williams, 2012) for further guidance on the estimation of measurement uncertainty.

10.5.1. For the purposes of this methodology, the following terms are utilized to describe uncertainty (JCGM 100:2008):

a. **Uncertainty (of measurement)**: parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand.

b. **Absolute uncertainty**: uncertainty expressed in the same units as the measured quantity.

c. **Relative uncertainty**: uncertainty of the result of a measurement expressed as a ratio or percentage, calculated by dividing the absolute uncertainty by the measured value.

d. **Standard uncertainty**: uncertainty of the result of a measurement expressed as a standard deviation.

e. **Standard error**: standard deviation of the sampling distribution of a statistic (often the mean).[76]

---

[76] Note that while the standard error can be thought of as a type of standard uncertainty, there is a difference between the standard deviation (standard uncertainty) associated with a population or sample of observations, and the standard deviation (standard error) associated with a statistic (e.g. the mean) calculated from the sample. Importantly, note that the standard error falls as the sample size increases whereas the standard deviation will tend to remain the same.

f. **Combined uncertainty**: uncertainty of the result of a measurement when that result is obtained from the values of a number of other quantities.

g. **Total uncertainty**: combined standard uncertainty.

h. **Expanded uncertainty**: quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand.[77] The expanded uncertainty is obtained by multiplying the total uncertainty by a numerical factor (i.e. the coverage factor) determined based on the level of confidence desired.

i. **Coverage factor**: numerical factor used as a multiplier of the combined standard uncertainty in order to obtain an expanded uncertainty (see also table 10.3).

j. **Type A evaluation (of uncertainty)**: method of evaluation of uncertainty by the statistical analysis of a series of observations.

k. **Type B evaluation (of uncertainty)**: method of evaluation of uncertainty by means other than the statistical analysis of a series of observations (e.g., by literature sources or expert judgement).

Table 10.3: Common coverage factors for the calculation of expanded uncertainty in the case of the normal distribution.

Level of confidence p (%)	Coverage factor k_p (unitless)
68.27	1.00
80.00	1.28
90.00	1.64
95.00	1.96
95.45	2.00
99.00	2.58
99.73	3.00

10.5.2. The CO_2 Removal Supplier shall determine the standard uncertainty of all parameters contributing to the overall uncertainty of the net CO_2 removal activity as further defined in subrules a-c.

---

[77] The fraction may be viewed as the coverage probability or level of confidence of the interval. Note that to associate a specific level of confidence with the interval defined by the expanded uncertainty requires explicit or implicit assumptions regarding the probability distribution characterized by the measurement result and its combined standard uncertainty. The level of confidence that may be attributed to this interval can be known only to the extent to which such assumptions may be justified.

a. The list of parameters for which standard uncertainty is determined shall include at least C_{stored}, $C_{baseline-[field]}$, $E_{project}$, (as defined in rule 5.3.1), as well as all their significant dependent parameters (see subrule c).

b. The determination of standard uncertainty shall be based on appropriate and scientifically justifiable sources of information as further defined in rule 10.5.11.

c. The CO_2 Removal Supplier may omit any or all of the following parameters from the quantification of uncertainty:

   i. The parameters C_{loss}, $C_{baseline-[feedstock]}$, and $E_{leakage}$. For these parameters, the quantification requirements set in this methodology are deemed to result in sufficiently conservative values, such that further deductions due to uncertainty are not necessary.

   ii. Any mathematical or scientific constants (e.g. molecular weights), and default values (e.g. the ancillary land use factor in eq. 8.1) included in this methodology.

For the purposes of calculating combined uncertainties, the CO_2 Removal Supplier may assume that the standard uncertainty of the omitted parameters is equal to zero.

10.5.3. The CO_2 Removal Supplier shall determine the parameters detailed in subrules a-d describing the overall uncertainty of the net CO_2 removal activity.

a. The total uncertainty, $u_c(CORC)$, shall be calculated as follows (see rule 10.5.2 c for parameters that may be omitted).

$$u_c(CORC) = \sqrt{u_c(C_{stored})^2 + u_c(C_{loss})^2 + u_c(C_{baseline})^2 + u_c(E_{project})^2 + u_c(E_{leakage})^2} \tag{10.1}$$

b. The expanded uncertainty, $U_c(CORC)$, shall be calculated as follows:[78]

$$U_c(CORC) = 1.28 \times u_c(CORC) \tag{10.2}$$

c. The relative expanded uncertainty, $U_r(CORC)$, shall be calculated as follows:

$$U_r(CORC) = \frac{U_c(CORC)}{C_{stored} - C_{loss} - C_{baseline} - E_{project} - E_{leakage}} \tag{10.3}$$

d. The factor of conservativeness, F_c, shall be calculated as follows:

$$F_c = max(0,\ 100\% - U_r(CORC)) \tag{10.4}$$

---

[78] The coverage factor 1.28 in this equation corresponds to a confidence interval of 80% (subject to the assumption that the underlying distribution is normal).

Variable	Description	Unit
$u_c(CORC)$	Combined standard uncertainty of the net amount of CO_2 equivalents removed by the enhanced weathering activity.	tCO_2e
$u_c(C_{stored})$	Combined standard uncertainty of the parameter C_{stored} (as defined in rule 5.3.1).	tCO_2e
$u_c(C_{baseline})$	Combined standard uncertainty of the parameter $C_{baseline}$ (as defined in rule 5.3.1).	tCO_2e
$u_c(C_{loss})$	Combined standard uncertainty of the parameter C_{loss} (as defined in rule 5.3.1).	tCO_2e
$u_c(E_{project})$	Combined standard uncertainty of the parameter $E_{project}$ (as defined in rule 5.3.1).	tCO_2e
$u_c(E_{leakage})$	Combined standard uncertainty of the parameter $E_{leakage}$ (as defined in rule 5.3.1).	tCO_2e
$U_c(CORC)$	The expanded uncertainty of the net amount of CO_2 equivalents removed by the enhanced weathering activity	tCO_2e
$U_r(CORC)$	The relative expanded uncertainty of the net amount of CO_2 equivalents removed by the enhanced weathering activity	%
F_c	Factor of conservativeness used to discount the Output volume issued as CORCs, in accordance with rule 5.3.1.	%

10.5.4. The CO_2 Removal Supplier shall establish a parameter hierarchy listing all of the dependent parameters (uncertainty contributors) for the top-level parameters C_{stored}, C_{loss}, $C_{baseline}$, $E_{project}$, and $E_{leakage}$ in an organized fashion, as further detailed in subrules a and b.

a. The parameter hierarchy shall clearly identify all dependent parameters contributing to the uncertainty of the top-level parameters in the CO_2 Removal Supplier's specific implementation of the ERW activity (i.e. taking into account, for example, that the parameters contributing to C_{stored} depend on the chosen quantification method).

b. The CO_2 Removal Supplier may choose a suitable representation for the parameter hierarchy, such as the example given in table 10.4, or a cause and effect diagram such as in EURACHEM-CITAC Guide CG 4, Appendix D (Ellison, S L R & Williams, 2012).

Table 10.4. Example of a hierarchy of parameters contributing to uncertainty of the parameter $E_{project}$.

Level 0 component	Level 1 contributor	Level 2 contributor	Level 3 contributor	Level 4 or more
$E_{project}$	Operation emissions	$E_{sourcing}$	Emission factor (EF_i) Activity data (AD_i) Allocation factor (AF_i)	
		$E_{transport}$		
		$E_{application}$		
	Embodied emissions	E_{infra}	WBLCA[a]	
		E_{dLUC}	CS	C_{veg}
				C_{DOM}
				SOC

Level 0 component	**Level 1 contributor**	**Level 2 contributor**	**Level 3 contributor**	**Level 4 or more**
			A	
			$E_{conversion}$	

[a] Note that 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.

10.5.5. The CO_2 Removal Supplier shall determine standard uncertainty utilizing appropriate and scientifically justifiable sources of information for each type of parameter (measured, estimated, or calculated; see rule 10.4.4), as further detailed in subrules a-c.

a. For **measured** parameters, the CO_2 Removal Supplier shall utilize one or several of the following sources of data uncertainty:

   i. statistical analysis of repeated measurements;

   ii. previous measurement data;

   iii. measurement device manufacturer’s specifications;

   iv. data provided in calibration and other certificates; and

   v. laboratory results from laboratories accredited under ISO 17025 or following equivalent evidenced practices (see rule 10.3.4).

b. For **estimated** parameters, the CO_2 Removal Supplier shall utilize one or several of the following sources of data uncertainty:

   i. uncertainties obtained from peer-reviewed publications or other similar credible sources (such as regulatory data, public databases, etc.);

   ii. uncertainties assigned based on quantitative procedures defined in peer-reviewed publications or other similar credible sources (such as regulatory data, public databases, etc.);[79] and

   iii. expert knowledge or judgement.

c. For **calculated** parameters, the CO_2 Removal Supplier shall determine the uncertainty based on a combination of the uncertainty of its dependent parameters (see rule 10.5.9).

10.5.6. To determine the total uncertainty, the CO_2 Removal Supplier shall comprehensively account for the identified sources of uncertainty as further detailed in subrules a and b.

---

[79] For example, through utilizing the pedigree matrix approach defined in the GHG Protocol guidance for Quantitative Inventory Uncertainty. This involves using the pedigree matrix approach based on qualitative indicators to compute the parameter's geometric standard deviation and propagating its uncertainty using a Taylor series expansion.

a. The CO_2 Removal Supplier shall, to the extent feasible, account for all sources of uncertainty identified in the uncertainty assessment (see rule 10.2.1 and table 10.1).[80]

    i. The CO_2 Removal Supplier may omit identified sources of uncertainty for which quantification is not possible or feasible with the available data and information, and for which no other reasonable estimate of uncertainty can be made.[81]

    ii. Uncertainty components arising from different sources should not be "double counted". In particular, when conducting a Type A uncertainty evaluation, additional uncertainties arising from a Type B evaluation should be included as independent components of the combined standard uncertainty only to the extent that the additional component does not contribute to the observed variability of the observations.[82]

b. Evaluations of uncertainty shall be based on all available information, and utilize quantitative data to the maximum extent possible.

    i. The uncertainty contributions for measured parameters shall be quantified using statistical analysis of repeated measurements wherever feasible (Type A evaluation).

    ii. The uncertainty contributions for modeled parameters (e.g. parameters quantified utilizing an ERW simulation model, see section 12) shall include uncertainties arising from the simulation itself (e.g. as a result of inaccurate input values), as well as uncertainties associated with imperfect treatment of modeled phenomena.[83]

    iii. Where quantitative data for the determination of uncertainty is not available or sufficient, the CO_2 Removal Supplier shall transparently document and

---

[80] For example, the total uncertainty for a measured parameter might include contributions due to random errors (e.g. resulting from variability of the soil or imprecision of the measurement device) as well as systematic errors (e.g. due to instrument drift or sample pretreatment). The former can be quantified through statistical analysis (Type A evaluation), while the latter e.g. from calibration records or other QA/QC documentation (Type B evaluation).

[81] Such uncertainties might include e.g. uncertainties due to gaps in the scientific understanding of the weathering process itself or other "unknown unknowns", or similar inherent biases (see also discussion in section 10.1)

[82] For example, when the standard uncertainty of a parameter is obtained via statistical analysis of a sample of repeat measurements (Type A evaluation), the random errors arising from the measurement device (device precision) contribute to the overall variability in the observations, and therefore need not be separately added as an independent component of uncertainty. However, potential systematic errors (e.g. instrument drift), determined e.g. through calibration records, would need to be added as an independent uncertainty contribution.

[83] For example, in an ERW simulation model, uncertainties can stem from the use of inaccurate input values, which can be rather straightforwardly quantified e.g. through Monte Carlo simulations. However, additional uncertainty can result from the imperfect treatment of relevant biogeochemical processes in the model itself. Such uncertainties might not be adequately captured in a Monte Carlo simulation, and often additional quantification is necessary (e.g. validation through comparing modeled results to empirically measured results to estimate root mean square error).

justify choice of values, sources of data, expert elicitation, and assumptions made.

10.5.7. Uncertainty estimates for a given parameter x obtained from an evaluation of the statistical dispersion of repeated measurements shall be quantified as the standard uncertainty $u(x)$ of the parameter x. In particular, this standard uncertainty can, depending on the quantity of interest, refer to the observed (sample) standard deviation, or the standard deviation of the sampling distribution (i.e. the standard error) of a statistic (e.g. the mean or median) calculated from the data as further defined in subrules a and b.[84]

a. When expressing the uncertainty in single measurements, or the uncertainty associated with a particular sample (as opposed to the population from which the sample is drawn),[85] the sample standard deviation is used.

b. When expressing the uncertainty of a statistic calculated from the sample, the standard error of the statistic is used. In particular, for expressing the uncertainty of average values obtained through the calculation of the arithmetic mean, the standard error of the mean is used.

Example: Consider a set of 100 measurements of soil cation concentration (e.g. [Mg^{2+}]) measurements over a group of fields, with an observed mean of 2500 ppm and a standard deviation of 500 ppm. Now, on average, the result of a single measurement of [Mg^{2+}] is 2500 ppm ± 500 ppm (i.e. a relative uncertainty of 20%). However, one is often more interested in the uncertainty of the mean itself rather than that of a single measurement (for example, if using the mean Mg concentration to assess the total Mg stock in the fields). In this case, the quantity of interest is the standard error of the mean, which can be estimated as

$$u(\overline{[Mg^{2+}]}) \approx \frac{u([Mg^{2+}])}{\sqrt{n}} = \frac{500\,ppm}{\sqrt{100}} = 50\,ppm,$$

Where $u(\overline{[Mg^{2+}]})$ is the standard uncertainty in the mean Mg^{2+} concentration, $u([Mg^{2+}])$ is the observed standard uncertainty in the sample, and n is the number of samples. In other words, if one were to obtain *another* set of 100 measurements and calculate a new mean from *that* set of observations, and repeat the process many times, the standard uncertainty in the set of means thus obtained would be approximately 50 ppm, considerably lower than the observed sample standard deviation of the single data sample.

---

[84] Note that the standard uncertainty can be thus different for different parameters or statistics calculated from the same underlying data. For further information on the difference between standard deviation and standard error, see e.g. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 3: Uncertainties, Box 3.0A (pp. 3.13–3.14)

[85] For example, when sampling a plot of land for a particular soil parameter (e.g. mean magnesium concentration), one is usually not ultimately interested in the mean of any particular sample of data points, but rather in the mean across the entire plot of land from which the sample is drawn (the underlying population). The mean will vary from sample to sample, but any given sample mean will be an *estimate* of the population mean.

10.5.8. Uncertainty estimates obtained from external sources (i.e. based on expert judgement, previous measurement data or other sources defined in subrules 10.5.5 a and b, except cases falling under the purview of rule 10.5.6) shall, where necessary, be converted to standard uncertainty as further detailed in subrules a-c.

a. Where an uncertainty estimate of a parameter x is reported as limits with a specified level of confidence p (that is, values reported in the form of $x \pm a$ at p% confidence), the standard uncertainty $u(x)$ of the parameter x is obtained by dividing the reported uncertainty range a by the coverage factor k_p (see table 10.3) corresponding to the reported level of confidence p, i.e. as $u(x) = a/k_p$.[86]

b. Where an uncertainty estimate of a parameter x is reported as limits without a specified level of confidence (that is, merely in the form of $x \pm a$ without level of confidence), the standard uncertainty is obtained as follows.

   i. In cases where the underlying distribution is stated or otherwise known to such an extent that the omitted level of confidence can be determined, the uncertainty shall be determined as detailed in subrule a.

   ii. In cases where the underlying distribution is unknown or poorly characterized,[87] and there is limited or no reason to believe that any part of the specified range is more likely than another, CO_2 Removal Supplier may assume a rectangular distribution and use the value $u(x) = a/\sqrt{3}$ as the standard uncertainty in the parameter x.

   iii. In cases where the underlying distribution is unknown or poorly characterized, but there is justifiable reason to believe that extreme values (i.e. values near the ends of the reported range) are unlikely, the CO_2 Removal Supplier may assume a triangular distribution and use the value $u(x) = a/\sqrt{6}$ as the standard uncertainty in the parameter x.

c. Where an estimate of the uncertainty of a parameter x is made based on expert judgement, and directly estimating the standard uncertainty (standard deviation) is not possible, then an estimate shall be made of the maximum deviation $x \pm a$ which could reasonably occur in practice. The standard uncertainty $u(x)$ of the parameter x shall then be obtained as detailed in subrule b.

10.5.9. In cases where the quantification of uncertainty of a parameter requires combination of uncertainties from other (dependent) parameters, the CO_2 Removal Supplier shall determine the combined uncertainty as further detailed in subrules a and b.

---

[86] Note that the value of the coverage factor depends not only on the level of confidence, but also on the underlying distribution of values, and the values in table 10.3 refer to the normal distribution in particular. Where uncertainty is reported as a confidence interval without specifying the distribution, the normal distribution may be assumed.

[87] In certain cases, it may be possible to estimate only the plausible upper and lower limits for a parameter, without knowledge about the possible values of the parameter inside the interval.

a. The combination of uncertainties shall be based on the parameter hierarchy described in rule 10.5.4, and proceed combining the uncertainty of parameters lower in the hierarchy to estimate the combined uncertainty of parameters higher in the hierarchy.

b. To determine the combined uncertainty, the CO_2 removal supplier shall utilize one or several of the following principal methods for propagating measurement uncertainty:

   i. Propagation of uncertainty through local expansion, including in particular the law of propagation of uncertainty (see rules 10.5.10 and 10.5.11).

   ii. Propagation of uncertainty based on repeated random sampling of input data or distributions, including in particular Monte Carlo simulations and related methods such as bootstrapping (see rule 10.5.12).

   iii. Propagation of uncertainty based calculation of a posterior probability distribution utilizing Bayesian inference (see rule 10.5.13).

10.5.10. For the purposes of obtaining a combined standard uncertainty utilizing local expansion methods, including in particular the law of propagation of error, the following rules apply.

a. The combined uncertainty shall be quantified through utilization of local linear or higher-order approximations (e.g. a first-order Taylor series expansion) to propagate the uncertainties of the input parameters through the measurement function to obtain an explicit estimate of the variance of the measurand (see also rule 10.5.10 for formulae specifically related to the law of propagation of error).

   i. The estimated variance shall be expressed at least in terms of the standard uncertainties of the input parameters, and their associated sensitivity coefficients (partial derivatives of the measurand with respect to the input parameters).[88]

   ii. Where possible, the estimated variance should include the appropriate covariance terms for correlated input parameters.[89]

b. The combined standard uncertainty shall be quantified as the positive square root of the estimated variance.

c. The CO_2 Removal Supplier shall provide thorough documentation of the expansion method utilized, which shall at least include:

   i. A general description of the model including the functional relationship modeled and the method used for propagating uncertainties;

---

[88] Note that besides the standard uncertainties and sensitivity coefficients, the expansion might additionally include other quantities, such as covariance terms for correlated inputs.

[89] Covariance terms can be difficult or impossible to quantify if correlated parameters are not measured jointly (e.g. from the same soil sample). Practically speaking, covariance terms should be included in the computation only if they have been estimated from sufficient data (Ku, 1966).

ii. The explicit mathematical formulae used for propagation of uncertainty;

iii. definition of all sensitivity coefficients (partial derivatives), standard uncertainties, and other input parameters; and

iv. description of all modelling assumptions (e.g. local linearity or independence of inputs), along with their justification based on scientific literature, pre-existing data, measurement information, or other scientific rationale.

10.5.11. For the purposes of obtaining the combined standard uncertainty utilizing the law of propagation of uncertainty, the following rules apply:

a. All uncertainty contributions shall be expressed as standard uncertainties (i.e. as standard deviations) before combination, except in cases where relative uncertainties are combined in the special cases detailed in subrules c and d. This may involve conversion to standard uncertainty from some other measure of dispersion (see rule 10.5.8).

b. To calculate the combined standard uncertainty, the CO_2 Removal Supplier may utilize the simplified variance formula, defined as follows in the EURACHEM-CITAC Guide CG 4, section 8.2.2 (Ellison, S L R & Williams, 2012):

$$u_c(y) = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial y}{\partial x_i}\right)^2 u(x_i)^2} \qquad (10.5)$$

c. As a direct consequence of the simplified variance formula in equation 10.5, the following formulas apply when variables are **combined through sum or difference**, i.e. if $y = x_1 \pm x_2 \pm ... \pm x_n$:

i. The combined *standard* uncertainty is

$$u_c(y) = \sqrt{u(x_1)^2 + u(x_2)^2 + ... + u(x_n)^2} \qquad (10.6)$$

ii. The combined *relative* uncertainty is

$$u_{c,r}(y) = \frac{\sqrt{\left(u_r(x_1)\cdot x_1\right)^2 + \left(u_r(x_2)\cdot x_2\right)^2 + ... + \left(u_r(x_n)\cdot x_n\right)^2}}{\left|x_1 + x_2 + ... + x_n\right|} \qquad (10.7)$$

a. As a direct consequence of the simplified variance formula in equation 10.5, the following formulas apply when variables are **combined through product of quotient**, i.e. if $y = x_1 x_2 ... x_n$ or $y = x_1 x_2 ... x_k/(x_{k+1} ... x_n)$:[90]

i. The combined *standard* uncertainty is

$$u_c(y) = |y|\sqrt{\left(\frac{u(x_1)}{x_1}\right)^2 + \left(\frac{u(x_2)}{x_2}\right)^2 + ... + \left(\frac{u(x_n)}{x_n}\right)^2} \qquad (10.8)$$

---

[90] Note that this does not apply to division in general (e.g. when the numerator or denominator is a sum of terms rather than a product of terms).

ii. The combined *relative* uncertainty is

$$u_{c,r}(y) = \sqrt{u_r(x_1)^2 + u_r(x_2)^2 + ... + u_r(x_n)^2} \tag{10.9}$$

d. In cases where independence of the dependent parameters x_i cannot be assumed, or the nonlinearity of the parameter y is significant, the CO_2 Removal Supplier should, where possible, utilize alternate methods to determine uncertainty, or a more accurate version of the law of propagation of error.[91] Such methods could include e.g. jointly measuring correlated quantities (e.g. from the same soil core) and utilizing bootstrapping on the joint probability distribution, or a more advanced propagation formula (including covariances) to determine the combined uncertainty.[92] In particular, these alternate methods should be considered when either of the below conditions occur.

  i. Two or more dependent variables are or can be expected to be correlated (i.e. the variables x_i are not all independent); or

  ii. the relative uncertainty in one or several of the the dependent parameters x_i is 30% or greater.[93]

Variable	**Description**	**Unit**
y	A parameter calculated from depending parameters $x_1, x_2, ..., x_n$, calculated as $y = f(x_1, x_2, ..., x_n)$ for some given function f.	Varies based on data
x_i	A dependent parameter utilized in the calculation of another parameter y. The index $i = 1, 2, ..., n$ is used to distinguish different parameters.	Varies based on data
$u(x_i)$	Standard uncertainty of the parameter x_i.	Varies based on data
$u_c(y)$	Combined standard uncertainty of the parameter y.	Varies based on data
$u_r(x_i)$	Relative uncertainty of the parameter x_i, calculated as $u(x_i) = \frac{u(x_i)}{\lvert x_i \rvert}$	%

---

[91] The variance formula is a first order simplification which neglects any covariances between the dependent variables, as well as all higher order terms. In practice, neglecting covariances between input variables may not always be justified (e.g. soil bulk density can be correlated with soil inorganic carbon content). The importance of higher order terms (i.e. terms proportional to 2nd and higher order derivatives of the parameter y) depends on the magnitude of the uncertainties in the dependent parameters x_i. When the uncertainties in the dependent parameters are small enough, the higher order terms can be neglected with little impact to the result.

[92] For more accurate versions of the variance formula (including higher order terms and covariances), see e.g. JCGM 100:2008, sections 5.1.2 and 5.2.2. Note, however, that fully determining all covariances between input parameters may not be possible or feasible in practice.

[93] For further discussion, see e.g. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 3.2.3 Methods to combine uncertainties.

Variable	Description	Unit
$u_{c,r}(y)$	Combined relative uncertainty of the parameter y, calculated as $u_{c,r}(y) = \frac{u_c(y)}{\lvert y\rvert}$	%

Remark: Note that the variance formula in equation 10.5 is defined in terms of standard uncertainties ($u(x_i)$). At times, it can be useful to combine *relative* uncertainties instead of *standard* uncertainties. To determine the correct formulas for combination of relative uncertainties, the variance formula can be utilized to calculate the combined relative uncertainty, i.e. the quantity $u_{c,r}(y) = \frac{u_c(y)}{\lvert y\rvert}$. In the special cases where the calculated parameter y can be expressed as a simple sum, difference, product, or quotient, the results of this calculation are given in rule 10.5.11.

Example: Soil bulk density

$$BD = \frac{M_{solids}}{V_{soil}}$$

can be determined based on measurements of the mass of solid soil particles (M_{solids}) in a given volume of soil (V_{soil}). The combined standard uncertainty in the bulk density, $u_c(BD)$, can be determined from the standard uncertainties in the measured variables ($u(M_{solids})$ and $u(V_{solids})$ based on the variance formula as follows. First, set

$$y = BD, \qquad \frac{\partial y}{\partial M_{solids}} = \frac{1}{V_{soil}}, \qquad \frac{\partial y}{\partial V_{soil}} = -\frac{M_{solids}}{V_{soil}^{2}},$$

and calculate the uncertainty as

$$u_c(BD) = \sqrt{u(M_{solids})^2\left(\frac{1}{V_{soil}}\right)^2 + u(V_{solids})\left(-\frac{M_{solids}}{V_{soil}^{2}}\right)^2}$$, or equivalently as

$$u_c(BD) = BD\sqrt{\left(\frac{u(M_{solids})}{M_{solids}}\right)^2 + \left(\frac{u(V_{solids})}{V_{soil}}\right)^2}$$

10.5.12. For the purposes of obtaining a combined standard uncertainty utilizing repeated random sampling of input data or distributions (i.e. utilizing Monte Carlo simulations and related approaches), the following rules apply:

a. The combined uncertainty shall be quantified through utilization of a probabilistic model where repeated random sampling (or resampling[94]) of input data or

---

[94] In statistics, resampling refers to the creation of new samples based on a previous observed sample. This is the basis of e.g. the bootstrapping approach, where resampling (with replacement) from the original sample is used to estimate the sampling distribution of a statistical estimator.

distributions is employed to propagate measurement uncertainties, model uncertainties, and other input variability through the model to obtain an explicit empirical probability distribution of values reasonably attributable to the measurand.[95]

b. The combined standard uncertainty shall be quantified as the standard deviation of the resulting simulated or resampled distribution of the measurand.

c. The CO_2 Removal Supplier shall provide thorough documentation of the probabilistic model employed, which shall at least include:

    i. a general description of the model including the simulation or resampling algorithm used and how uncertainty sources are propagated;

    ii. a step-by-step outline of the modelling process flow, including key modeling parameters (e.g. number of iterations/samples utilized) and relevant convergence diagnostics;

    iii. definition of all model parameters, input distributions, and other inputs, including references to the scientific literature, supporting data or other sources used for their selection;

    iv. description of all modelling assumptions (e.g. the choice of input distributions), along with their justification based on scientific literature, pre-existing data, measurement information, or other scientific rationale.

10.5.13. For the purposes of obtaining a combined standard uncertainty utilizing Bayesian inference, the following rules apply:

a. The combined uncertainty shall be quantified through utilization of a probabilistic model where Bayes' theorem is used to combine information from measurements with prior information about the possible (or likely) distribution of values of the measurand to generate an explicit posterior probability distribution describing an updated probabilistic estimate of values reasonably attributable to the measurand.[96]

b. The combined standard uncertainty shall be quantified as the standard deviation of the resulting Bayesian posterior probability distribution for the measurand.

c. The CO_2 Removal Supplier shall provide a thorough documentation of the probabilistic model utilized, which shall at least include:

---

[95] For general guidance on Monte Carlo simulations and related approaches, the CO_2 Removal Supplier should refer to applicable standards, particularly ISO/IEC Guide 98-3:2008/Suppl 1:2008, as well as relevant scientific literature and technical guidance (Davison & Hinkley, 1997; Efron & Tibshirani, 1994; Papadopoulos & Yeung, 2001; Shi et al., 2015; J. Zhang, 2021). Furthermore, there exist several online tools and software packages relevant for uncertainty estimation utilizing the Monte Carlo approach, such as the simple NIST uncertainty machine (Lafarge & Possolo, 2015), as well as the more extensive Monty package for simulating geochemical data in the context of ERW (Baum et al., 2024).

[96] For general guidance on constructing Bayesian models, the CO_2 Removal Supplier should refer to applicable standards (e.g. ISO/TR 13587:2012, and applicable parts of ISO/IEC Guide 98-3:2008/Suppl 1:2008), as well as relevant scientific literature and technical guidance (Baum et al., 2024; Brus et al., 2022; Clark, 2005; Gelman et al., 2020; Kruschke, 2015; McElreath, 2020).

i. a general description of the model including algorithms utilized and how uncertainty sources are propagated

ii. a step-by-step outline of the modelling process flow, including key modeling parameters (e.g. metrics related to the sampling algorithms utilized) and relevant convergence diagnostics;

iii. definitions of all model parameters, prior distributions, likelihood functions, and other inputs, including references to the scientific literature, supporting data or other sources used for their selection;

iv. description of all modelling assumptions (e.g. the choice of prior distributions), along with their justification based on scientific literature, pre-existing data, measurement information, or other scientific rationale.

11. Sampling, Measuring, and Quantification Approaches

11.1. Homogeneous Strata, Application, Evaluation, and Control Sites

Production Facilities and total project areas are composed of one or more homogeneous strata which share similar agricultural, application, and soil characteristics defined in rule 11.1.1. Each stratum is further subdivided into application and control sites (see figure 3.2). The designated control site will be subject to the monitoring protocols, as will a subset of the application site selected as the evaluation area.

Stratification is used to ensure that comparisons between application and control sites are scientifically valid, and that observed differences in carbon removal or environmental impact can be attributed to the ERW activity rather than underlying variability in site conditions. In practice, the number of control sites per homogeneous stratum can be as low as 1 (although a larger number is recommended as a backup in case of unexpected land use change, contamination, or other confounders) as long as the following rules are adhered to:

11.1.1. The CO_2 removal supplier shall apply a stratified sampling strategy by identifying “homogeneous strata” made up of fields with similar agronomic and soil properties defined in subrules a-d.

  a. When assigning fields to homogeneous strata, the CO_2 removal supplier shall ensure that each stratum is consistent with respect to at least the following criteria:
    - **Climatic conditions**: a single homogeneous stratum shall fall within a single Köppen-Geiger climate zone including precipitation and temperature subgroups (Beck et al., 2018).
    - Applied ERW **feedstock type**, application density, and timing of application shall be consistent across all fields within a stratum.
    - **Soil properties**: a single homogeneous stratum shall contain only a single soil type, as defined either by the same WRB Reference Soil Group[97] and principal qualifiers across the stratum, or by the USDA Soil Taxonomy[98] at the Subgroup level. Alternatively, the soil texture shall be similar, such that the percentages of its components (sand, silt, clay) fall within one standard deviation of the distribution found across the Production Facility.
    - **Agronomic practice**: tillage, irrigation, past and present fertilizer application or liming, as well as past ERW application shall be consistent within each homogeneous stratum. In case of unexpected changes in agricultural practice during a monitoring period, these

---

[97] IUSS Working Group WRB, 2022. World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps. 4th edition. International Union of Soil Sciences (IUSS), Vienna, Austria.

[98] USDA Natural Resources Conservation Service. Keys to Soil Taxonomy, 13th Edition. Washington, D.C.: United States Department of Agriculture, 2022.

changes shall be documented and their impact shall be evaluated in consultation with the Issuing Body.

b. Additionally, the strata should be similar with respect to crop type. Crops are subject to rotation during a given growing season but homogeneous strata should as much as possible be delineated in a way as to contain only one type of crop at any given time during a monitoring period.

c. Additionally, the strata should be similar with regards to the parameter measured in the chosen quantification approach for C_{stored}.

d. Additional quantitative parameters should be chosen to maximize similarity within strata, which include but are not limited to soil pH, pH buffering capacity, base saturation, CEC, SOC, SIC, slope, and other soil properties with relevance to feedstock weathering.

11.1.2. Similarity in quantitative parameters between fields for the purpose of identifying homogeneous strata (see rule 11.1.1) shall be determined by pre-application measurements of the relevant parameters (see also rule 9.4.4).

11.1.3. Each homogeneous stratum shall be divided into application and control site areas. Both control and the evaluation area (a more densely monitored subset of the application site) shall be monitored for C_{stored} using the same quantification and validation approaches. The minimum fraction of the area of each homogeneous stratum that must be covered by control site and evaluation areas is specified in table 11.1.

Table 11.1. Minimum requirements for the areal extent of control and evaluation per homogeneous stratum. Note that the evaluation area is the subset of the application site that is monitored for C_{stored} quantification and validation.

Stratum Size (ha)	Control Site Area	Evaluation Area
≤10	5%	5%
10-100	4%	4%
101-1,000	3%	3%
1,001-5,000	2%	2%
5,000+	1%	1%

11.1.4. Within strata, appropriate sampling strategies (e.g., split field, randomized control, grid sampling) shall be employed in assigning plots as control sites and application sites in order to avoid systematic patterns between control and application sites.

Control Sites

Control sites are plots of land within the Production Facility to which Enhanced Rock Weathering is not applied but which are monitored to quantify $C_{baseline}$ for the CORC equation (see figure 5.1) as described in section 6.2. Thus, the purpose of control sites is to enable quantification of the baseline scenario, which is equivalent to the counterfactual (or business-as-usual) scenario.

11.1.5. Control sites shall be treated in the same way as the agricultural plots that are part of the Production Facility used to be treated prior to and would have been treated in the absence of the Enhanced Rock Weathering activity, including in the following regards:

- *Liming*: limestone rock shall be applied at the same frequency and quantities to control sites as in the counterfactual scenario, i.e., the business-as-usual case at a given location before the ERW activity.
- *Fertilizer use*: Enhanced Rock Weathering can replace or reduce the use of traditional fertilizers. Fertilizers should be applied to control sites at the frequency and quantity of the counterfactual scenario.
- *Agronomic practices*: if the Enhanced Rock Weathering activity leads to any changes in agronomic practices (e.g., frequency of tillage), these practices shall be implemented on control sites as in the counterfactual scenario

11.1.6. In cases where liming applies as a counterfactual (would have been part of business as usual) but a carbon dioxide removal supplier cannot correct for counterfactual liming practices by liming the control site, a conservative estimate of the counterfactual carbon dioxide removal must be made and added to $C_{baseline}$ (rule 5.3.1).

- This conservative estimate shall take into account the amount of counterfactual liming based on documented records and assume complete carbonic-acid weathering of all limestone that would have been deployed in the counterfactual scenario as per the following equation, i.e., assuming 1 mol of CO_2 sequestered per 1 mol of $CaCO_3$ equivalents (see equation 1.4) in limestone applied under the counterfactual scenario.
- This conservative estimate for CO_2 removed in the counterfactual liming scenario may be corrected for the loss terms in rules 6.3.3-6.3.11 prior to addition of the resulting value to $C_{baseline}$.

11.1.7. Control sites shall be selected in a way that minimizes contamination risk from application sites; e.g., control sites downhill of application sites are at risk to receive weathering material via surface-runoff.

11.2. Sampling

A proper sampling protocol is crucial to ensure representative and accurate measurements resulting in detectable weathering signals. This section describes the requirements for sampling within the homogeneous strata, which are comprised of application and control sites (see section 11.1 and figure 3.2).

Sampling tools

Soil sampling tools

Typical soil sampling tools include augers, tubes or cores and simple shovels. Augers are one of the most commonly used tools, available in various designs such as bucket, spiral, and Edelman augers, each suited for different soil textures. Soil cores provide intact soil columns that preserve natural stratification and bulk density. Piston corers can be useful for deeper profiles, as they minimize soil compression and disturbance during extraction. Tube samplers and split-tube samplers are often employed for undisturbed soil sampling, providing high-quality cores for laboratory analysis. Shovels and trowels, while convenient for quick soil sampling, are not precise enough for ERW projects, which require accurate control over sampling depth. In the context of this document, soil samples are expected to be cores that are later homogenized to integrate the soil between the soil surface and the bottom of the soil core sample. Such soil core samples can be used for several C_{stored} quantification approaches (section 11.2): CAT_{Ti}, CAT_{WM}, SIC_{soil}.

Soil water sampling tools

Soil water can exist in a myriad of tensions (tension-free or gravitational to hygroscopic water), and in a variety of locations within the soil matrix (micropore vs. macropore). Further, soil water flow paths differ as a function of soil moisture and may change from one precipitation event to the next. Thus, the chemical composition of soil water is naturally dynamic and spatially heterogeneous. It should be noted that the extraction of water from the soil matrix for the purpose of obtaining a true soil water sample is not a feasible objective (Essington, 2004). However, several tools exist that can be employed to obtain an estimation of the processes operating in the soil environment. It is important to note that for all tools, the volume of water collected is typically sporadic and inconsistent between replicates and that some studies show that vacuum tools show higher concentrations in comparison to tension-free samples and others vice versa (Barbee & Brown, 1986; Giesler et al., 1996; S. Buckingham et al., 2008). Nevertheless, given that tension-free tools are generally better at estimating solute export from the soil profile (i.e., leaching fluxes), they seem also to be the most appropriate tool for C_{stored} calculations, while vacuum-tools can be useful for understanding geochemical processes occurring at the micropore level.

The most widely used tools for soil pore water collection are **vacuum soil water sampling tools** such as **rhizon samplers** and **porous ceramic cups** (in some texts interchangeably called lysimeters). Both devices intend to imitate the suction of soil pore water by roots by applying a vacuum force to pull out soil pore water. Although effective and commonly utilized, care must be taken in regards to interpreting data collected from these tools. The porosity of the samplers will dictate what parts of the soil pore water will be collected. Rhizons typically have sub-micrometer pore sizes, which, if working properly, has the advantage of avoiding a filtering step before measurements. On the other hand, the small permeable tips can lead to selective sampling due to adsorption forces in the soil. Ceramic cups are more complex and come in different sizes. They can collect higher pore water volumes (few hundreds of millimeters) in comparison to the rhizons that can only collect 20 to 40 mL of water pulled into syringes. As ceramic cup tips typically have higher porosity (on the micron scale) than rhizon samplers, samples need to be filtered before most measurements to eliminate microorganism and solid particles using at least ≤0.45 µm (better 0.2 µm) filters. Vacuum soil water sampling tools collect water that is in the soil pore space at the time of sample collection and therefore results from these sampling methods represent a discrete snapshot in time rather than an integrated measurement of longer-term conditions.

Passively collecting soil water sampling tools like **vacuum-free lysimeters** (e.g., pan lysimeters) have been applied in various agronomic and ERW studies to measure leachate soil water. These devices collect soil drainage/leachate water into a closed sampler (such as a cup). Most designs include a relatively large sample chamber (e.g., several liters in volume). This means that chemical re-equilibration will occur inside the sample chamber due to air contact in between each sampling event (which could be days or even months apart, depending e.g. on the rain conditions and potential irrigation systems). As a consequence of these subsequent reactions, some parameters (e.g. pH and DIC) might no longer be representative of the soil pore chemistry by the time of collection and measurement. On the other hand, compared to vacuum tools, lysimeter samples integrate the cumulatively leached ions over longer periods of time. Samples collected in lysimeters require filtering before measurements (0.45 micron filters are recommended to eliminate microorganism and solid particles).

As a final subcategory, **cation exchange resins** (discussed in detail also in section 11.2, Approach 5 - CATresin) do not in fact collect soil water but are installed within the soil, where they directly capture cations dissolved in soil water via negatively charged surface sites. These captured cations can then be analysed after resin retrieval and elution with strong acids. Thus, cation exchange resins can also provide time-integrated measurements of leached cations over longer periods. Resin-based sensors now exist that can measure the amount of leached cations in-situ, enabling the creation of continuous time-series data on cation export. However, stronger resins may dissolve weathering feedstock, creating false positive weathering signals and at the time of this writing (06/2025), no peer-reviewed studies of resin use in ERW have been published.

11.2.1. For each quantification approach (section 11.2), appropriate and consistent sampling tools shall be used within a given monitoring period. Each sampling tool used (e.g. auger, lysimeter), shall be linked to (a) relevant monitored parameter(s) in the monitoring plan.

Definition of a soil sample

11.2.2. A soil sample shall consist of a number of subsamples that are combined to make up a representative, composite soil sample of the data point location where it is collected as further specified in subrules a-c:

a. One soil sample shall consist of at least 5 subsamples but should ideally consist of 15 or more subsamples. If less than 15 subsamples are taken, the CO_2 Removal Supplier shall justify this choice by demonstrating that appropriate statistical evaluation is possible with the applied number of subsamples.
b. Soil subsamples making up a single composite soil sample shall be collected within a radius of 5 to 15 m from a central point (which should be georeferenced).

c. Subsamples should then be homogenized to form a single composite sample per site and time point (t_0, t_1) that is then sent to analysis.

Definition of a soil water sample

11.2.3. A soil water sample shall be defined as the water (or dissolved ions collected from soil water) collected by a soil water sampling device (see above: Soil water sampling tools) at a given point in time (discrete samples from vacuum-based tools) or over a longer continuous period of time (integrated samples from passive tools or resins).

Sampling frequency

11.2.4. For quantification of C_{stored}, sampling and associated measurements shall be performed at least twice for each monitoring period at all designated control and application sites: 1) shortly before or after (depending on quantification approach) feedstock application (t_0); 2) at the end of the monitoring period (t_1). Note that these two measurement points are in addition to pre-application soil characterization measurements (see section 9.4), which may, however, be re-used for t_0 measurements in cases where t_0 is measured before feedstock application (rule 9.4.3).

11.2.5. Additional samples (between t_0 and t_1) may be taken at various times during the monitoring period to improve and inform data evaluation and operational decisions.

11.2.6. CDR quantification approaches based on soil water sampling do not inherently integrate the weathering signal between time points t_0 and t_1. In these cases, sampling frequency or duration shall be increased beyond t_0 and t_1 measurements in a way that ensures quantitative capturing of the weathering signal. This can be achieved by longer-term (weeks to months; Milliken et al., 2025) continuous sampling (for time-integrating sampling tools such as passive lysimeters) and/or higher sampling frequency (for non-time-integrating sampling tools such as vacuum-based soil water samplers). For more details, see the section on sampling tools.

Sampling density for C_{stored} quantification

11.2.7. For C_{stored} quantification, the number of soil or soil water samples (defined in rules 11.2.2 and 11.2.3) taken from application and control sites within each homogeneous stratum (section 11.1) shall be sufficiently large to enable the quantification of enhanced weathering signals at a statistically significant level (see rule 6.2.13) when comparing application and control sites within each homogeneous stratum. Additionally, a minimum number of samples per application and control site area within each homogeneous stratum shall be taken, following subrules a-c and the guidelines in table 11.2:

a. The minimum absolute amount of samples taken per evaluation area, application and control site, respectively, shall be three (3), with more samples required for larger homogeneous strata based on sampling density requirements scaling with stratum size as outlined in table 11.2. Note that the minimum sampling density guidelines outlined in table 11.2 follow a square-root decay function allowing for lower sampling density with increasing homogeneous-stratum area as follows, where *k* = *3* for soil samples and *k* = *1* for soil water samples:

$$Min.\ samples\ per\ ha\ = k\ /\ \sqrt{stratum\ size\ [ha]} \tag{11.1}$$

b. The minimum sampling density numbers derived from table 11.2 shall be rounded up to the next integer.

c. The samples per ha of homogeneous stratum required in table 11.2 shall be divided as follows:

- If the application site is divided into a more densely sampled evaluation area and a less-densely sampled remainder (sometimes referred to as 3-plot approach): ⅓ of the minimum required sample number shall be taken on the control site, ⅓ on the application site's evaluation area, and ⅓ on the remainder of the application site.
- If the application site is sampled evenly (i.e., the entire application site is used as evaluation area, sometimes referred to as 2-plot approach): ⅓ of the minimum required sample number shall be taken on the control site, ⅔ on the application site.

Table 11.2. Minimum sampling density required for quantification and validation of C_{stored} expressed as number of samples per area of homogeneous stratum taken on the stratum's control site(s), evaluation area, and non-evaluation area of the application site. The minimum required sampling density per ha decays as a function of stratum size according to eq.11.1. Note that a lower density applies to the validation approach (see rule 11.1.8).

Stratum Size (ha)	Soil samples per ha	Soil water samples per ha
10	0.949	0.316
50	0.424	0.141
100	0.300	0.100
500	0.134	0.045
1000	0.095	0.032
5000	0.042	0.014
>5000	etc.	etc.

Sampling depth

11.2.8. For each measurement approach (e.g., soil pore water, solid soil samples), the sampling depth shall be consistent across sampling events (e.g., t_0, t_1), at a given sampling site, and between control and application sites that are compared with each other (e.g., within a given sampling stratum or block).

11.2.9. The sampling depth for the quantification of ERW signals shall equal the depth of the near-field zone (NFZ). The depth of the NFZ shall be at least the smaller of i) the local groundwater table depth and, ii) the fixed depth of 20 cm. Where tillage is practiced, the fixed depth shall be the larger of 20 cm or 5 cm below the average tillage depth. Alternatively, sampling depth may be defined relative to soil horizons (rule 11.2.13).

11.2.10. “NFZ depth” has different implications for sampling for different quantification approaches (section 11.2):

a. For approaches based on bulk-soil sampling (CAT_{WM}, CAT_{Ti}), the NFZ depth shall represent the lower end of the depth range within which the weathering signal is integrated, whereas the upper end of that range is the soil surface. Bulk-soil samples should cover the vertical extent between soil surface and NFZ depth (i.e., base of the NFZ) to be representative of the entire NFZ and implicitly account for the loss terms $Loss_{adsorb}$, $Loss_{carbonate}$, and $Loss_{silicate}$ (see rules 6.3.6 - 6.3.8).
b. For approaches based on soil-water sampling ($CAT_{porewater}$, $BIC_{porewater}$), the NFZ depth shall represent the depth from which pore water should be sampled (e.g., lysimeter depth). Sampling at the NFZ depth (= base of the NFZ) is desirable because it implicitly accounts for the loss terms $Loss_{plant}$, $Loss_{adsorb}$, $Loss_{carbonate}$, and $Loss_{silicate}$ (see rules 6.3.6 - 6.3.8).
c. For the resin-based approach (CAT_{resin}), the resin should be installed to a depth equalling the NFZ depth. Sampling at the NFZ depth (= base of the NFZ) is desirable because it implicitly accounts for the loss terms $Loss_{plant}$, $Loss_{adsorb}$, $Loss_{carbonate}$, and $Loss_{silicate}$ (see rules 6.3.6 - 6.3.8).

11.2.11. In some situations and for some approaches, it may be desirable to take additional samples below the NFZ depth at the beginning and end of the monitoring period (t_0 and t_1), in order to avoid missing the weathering signal. Weathering signal determined on this basis may be taken into account to calculate C_{stored}.

11.2.12. As an alternative to the absolute NFZ depth specified in rule 11.2.10, the NFZ depth may be defined along natural soil horizons. E.g., if the bottom of horizon A is used, samples shall be taken to this depth regardless of the absolute depth (in cm) at various sampling sites across the field site. Sampling along soil horizons reduces the risk of mixing chemically and physically distinct soil layers and is expected to lead to better comparability of application and control site samples. If defining the NFZ depth relative to soil horizons, CO_2 removal suppliers shall at least sample to the middle of horizon A and care shall be taken that the horizon depth is chosen in a way that the sampling depth in the majority of samples remains at least at 10 cm or, where tillage is applied, at tillage depth plus 5 cm. When orienting NFZ depth along soil horizons, the CO_2 Removal Supplier should still record the absolute sampling depth (in cm) of each sample and consider the following rationales that also take into account local tillage depth:

a. Topsoil sampling (A), reflects nutrient and organic carbon fluxes, biological activity, and short-term weathering material reactions in the NFZ. If orienting sampling depth along soil horizons,
b. Sub-soil sampling (horizon B), reflects nutrient leaching and more stable carbon pools.

11.3. Quantification approaches

As of this writing (September 2025), there is no consensus on the best approach for quantification of gross CDR (C_{stored}) through ERW, but several approaches have been suggested (table 6.1) and successfully applied in scientific studies of ERW (Amann et al., 2020, 2022; Dietzen et al., 2018; Haque et al., 2019, 2020; Jariwala et al., 2022; Khalidy et al., 2021; McDermott et al., 2024; Milliken et al., 2025).

C_{stored} can be measured by tracking either the starting materials (reagents) or the end products of the weathering reaction (figure 1.1). As weathering progresses (i.e. hydrolysis and dissolution of weathering material), the resulting products are transported from the weathering zone (or near field zone – NFZ) to deeper layers, into the underground (far field zone – FFZ), eventually flowing into rivers, and ultimately oceans. An effective quantification approach for C_{stored} (and $C_{baseline\text{-}[field]}$) is one that can accurately quantify the rate at which the weathering signal leaves the NFZ while using an appropriate weathering signal, i.e., a parameter that represents an accurate proxy for inorganic carbon.

Table 11.3. Overview of sample pretreatment and analytical tools used for measurements in each approach.

Approach	Sample pre-treatment	Analytical tools
A1 - CAT_{WM}	Total digestion of soil with weathering material, e.g., dissolution with HCl + HNO_3 + HF as in ISO 14869-3:2017. Aqua regia (HNO_3 + HCl) digestion (ISO 54321:2020) may be applied alternatively if a) aqua regia can be demonstrated to digest the vast majority (>90%) of utilized feedstock, and b) a subset of measurements (at least 10% of samples for C_{stored} at a given time point) are done using the full digestion (ISO 14869-3:2017) protocol to account for secondary silicate losses.	Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), Inductively Coupled Plasma Mass Spectrometry (ICP-MS), Atomic Absorption Spectroscopy (AAS).
A2 - CAT_{Ti}	Total digestion of soil with weathering material, e.g., dissolution with HCl + HNO_3 + HF as in ISO 14869-3:2017. Aqua regia (HNO_3 + HCl) digestion (ISO 54321:2020) may be applied alternatively if a) aqua regia can be demonstrated to digest the vast majority (>90%) of utilized feedstock, and b) a subset of measurements (at least 10% of samples for C_{stored} at a given time point) are done using the full digestion (ISO 14869-3:2017) protocol to account for secondary silicate losses	Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), Inductively Coupled Plasma Mass Spectrometry (ICP-MS), Atomic Absorption Spectroscopy (AAS).
A3 - $CAT_{porewater}$	Filtration (if applicable) and acidification	Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), Inductively Coupled Plasma Mass Spectrometry (ICP-MS), Atomic Absorption Spectroscopy (AAS), *ex-situ* ion selective electrodes.

Approach	Sample pre-treatment	Analytical tools
A4 - $BIC_{porewater}$	Sample pre-treatment depends on the analytical method used, but typically involves filtration.	After acidification, bicarbonate and carbonate species content can be measured using an infrared gas analyser, or coulometry. Titrations are used for total alkalinity measurements.
A5 - CAT_{resin}	Ion-exchange resins adsorb cations (CAT) from soil pore-water. The cations can be eluted from the resin with a strong acid (e.g., HCl).	Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), Atomic Absorption Spectroscopy (AAS). Some tools might have sensors for automated signals.
A6 - SIC_{soil}	Method-dependent	There are direct and indirect methods (in order from higher to lower accuracy): direct methods include thermogravimetric analysis (TGA) and calcimetry; indirect methods include dry combustion (Leogrande et al., 2021).

Approach 1 - CAT_{WM}

The CAT_{WM} approach assesses the extent of weathering by quantifying the loss of chemical elements from the weathering material (feedstock) in the NFZ. This serves as a proxy for CO_2 sequestration by the part of the feedstock that has reacted and left the NFZ (i.e. not detectable at the sampling zone).

Chemical elements that are typically present in weathering materials and can be used as weathering reaction proxies include major cations such as Ca^{2+}, Mg^{2+}, K^+, and Na^+. Importantly, each positive charge corresponds to one sequestered CO_2 molecule —consequently, due to their different charges, each mole of calcium or magnesium (with two positive charges) sequesters two CO_2 molecules, while potassium and sodium (with one positive charge each) sequester one CO_2 molecule.

Calculations

After sample analysis (using the method described in table 11.3), cation content is typically given in mg_{CAT}/L_{sample}. This value must be normalized to the mass of soil used in the digestion to obtain a mass concentration in mg_{CAT}/kg_{soil} or ppm.

The CO_2 sequestration is estimated from the decrease of weathering material from the NFZ as indicated by the decrease in the major cation proxy during a monitoring period lasting from the beginning of the monitoring period (t_0, just after feedstock application) to its end (t_1) in application and control sites as follows:

$$F1 = BD_{soil} \times d \times A_{ext} \tag{11.2}$$

$$F2 = Mw_{CO2} / Mw_{CAT} \times n \tag{11.3}$$

$$C_{stored} = \Delta CAT_{application} = (CAT_{t0} - CAT_{t1})_{application} \times F1 \times F2 \tag{11.4}$$

$$C_{baseline-[field]} = \Delta CAT_{control} = (CAT_{t0} - CAT_{t1})_{control} \times F1 \times F2 \tag{11.5}$$

$$\Delta CAT_{WM} = \Delta CAT_{application} - \Delta CAT_{control} \tag{11.6}$$

Where:

Variable	Description	Unit
A_{ext}	The field area to which weathering feedstock was applied that is represented by the evaluated sample or set of samples, i.e., the area to which the weathering signal may be extrapolated to, i.e., the area within a homogeneous stratum to which weathering feedstock was applied. Note that therefore the value of A_{ext} will be the same for both C_{stored} (application sites, eq. 11.4) and $C_{baseline-[field]}$ (control sites, eq. 11.5)	m^2
BD_{soil}	Bulk density of soil (measured)	g_{soil}/m^3
d	Sampling depth = the depth the proxy signal is integrated over	m
Mw_{CO2}	Molecular weight of CO_2 = 44.01 g/mol	g_{CO2}/mol
Mw_{CAT}	Molecular weight of the measured cation	g_{CAT}/mol
n	CO_2 sequestration charge capacity of the cation considered (n = 2 for Ca and Mg, n = 1 for K and Na)	unitless
$F1$	Factor equaling the amount of soil (g_{soil}) in the extrapolation area (A_{ext}) taking into account the depth over which the sample integrated (d); multiplying with this factor therefore extrapolates the weathering signal per gram of soil to the field area this signal represents	g_{soil}
$F2$	Factor converting the weathering signal in grams cations to a signal in grams CO_2	g_{CO2}/g_{CAT}
CAT_i	Concentration of the selected major cation proxy at $i = t_0$ or $i = t_1$	g_{cation} / g_{soil}
$\Delta CAT_{application}$	Gross amount of carbon dioxide stored as carbonate and bicarbonate ions as measured as decrease in the major cation proxy within the NFZ of application sites (weathering signal) over the monitoring period, i.e., between t_0 and t_1	gCO_2
$\Delta CAT_{control}$	Amount of carbon dioxide stored as carbonate and bicarbonate ions on control sites as measured as decrease in the major cation proxy within the NFZ of control sites (weathering signal) over the monitoring period, i.e., between t_0 and t_1. Control sites represent the baseline of natural weathering that would have occurred also on application sites in the absence of the ERW activity	gCO_2
ΔCAT_{WM}	Baseline-corrected decrease in the NFZ-concentration of the cation proxy converted to amount of CO_2 removed during the monitoring period as quantified by the CAT_{WM} approach	gCO_2

When using the CAT_{WM} approach, CDR by enhanced weathering is indicated if the following two requirements are met:

1. $\Delta CAT_{application} > 0$: There should be a statistically significant net loss of chemical elements from the NFZ between the initial (t_0) and final (t_1) sampling periods in the application sites.
2. $\Delta CAT_{WM} > 0$: The weathering signal should be statistically significantly higher in the application sites compared to control sites, confirming that the measured change is due to actual material weathering.

A lack of these signals (i.e., a case where $CAT_{application} < 0$ and/or $\Delta CAT_{WM} < 0$) might indicate a lack of CDR and will be accounted for in this way with respect to carbon crediting. However, we note that such a lack of signal could also result from a lack of similarity between control and application sites, addition or subtraction of weathering material by runoff, measurement errors, and other uncertainty and variability drivers. Thus, all measurements should be evaluated and reported as part of the output audit, regardless of whether the conditions for crediting based on CAT_{WM} quantification are met. Comprehensive evaluation and reporting, including cases where no measurable change occurs, is essential for future avoidance of any false negatives, transparency, interpretation of variability, and comparability across sites and monitoring periods.

Applicable loss terms

Given that this approach measures the full removal of a proxy cation from the NFZ rather than directly quantifying carbonic acid weathering, additional discounts have to be made for non-carbonic acid dissolution ($Loss_{acid}$) and cation uptake into plant biomass ($Loss_{plant}$, rule 6.3.5). The loss pathways $Loss_{adsorb}$, $Loss_{carbonate}$, and $Loss_{silicate}$ are implicitly accounted for by this approach if soil samples integrate over the entire depth of the NFZ and are fully digested, but need to be corrected for if only part of the vertical extent of the NFZ is sampled. The FFZ loss terms $Loss_{rivers}$ and $Loss_{rivers}$ need to be accounted for.

11.3.1. The CO_2 Removal Supplier may use CAT_{WM} type measurements to quantify C_{stored} according to eqs. 11.2-11.6 and taking into account the approach-combination constraints in rule 9.5.2.

Approach 2 - CAT_{Ti}

The CAT_{Ti} approach is similar to the **CAT_{WM}** approach in many respects. This approach also assesses the extent of weathering by quantifying the loss of chemical elements from the weathering material (feedstock) and the NFZ. In addition to evaluating cation loss, immobile trace elements are used to determine the percentage of the feedstock that has dissolved relative to the total amount applied.

The same set of chemical elements is used as weathering reaction proxies, including major cations such as Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}. Additionally, non-mobile (or less mobile relative to the aforementioned ones) minor trace elements such as Ti^{2+}, Ni^{2+}, Rb^{2+} serve as additional proxies that document the lack of movement of the non-mobile part of the weathering material through the NFZ (Reershemius et al., 2023; Suhrhoff et al., 2024, 2025). This ensures that any change in the major cations measured in parallel is due to weathering rather than loss of unweathered material (e.g., due to run-off).

CAT_{Ti} requires the analysis of soil and/or feedstock cation composition using soil digestions and analytical instruments like ICP-MS or ICP-OES (table 11.3). The precise protocol for this approach as presented in eqs. 11.7-11.17 below, assumes the analysis of the following samples:

- Feedstock prior to deployment
- Baseline field soil samples prior to deployment of weathering materials
- Soil samples at the end of the monitoring period (t_1)

Alternative evaluation method

Instead of using feedstock analysis to determine the ratio of cations to immobile trace elements, CO_2 removal suppliers using the CAT_{Ti} approach can utilize the element ratios and cation concentrations found in post-application soil samples ($t_{0.1}$), which represent a mix of soil and feedstock. This requires a different set of equations than those presented in eqs. 11.7-11.17 based on the following set of samples:

- Soil samples immediately following deployment ($t_{0.1}$) before weathering
- Soil samples at the end of the monitoring period (t_1)

If the post-application soil samples are being used for t_0, then the calculations do not need to account for pre-application trace elements or prior monitoring periods. The weathering rate can be calculated based on the change in cation concentration relative to any changes in concentration of trace elements in the soil during the monitoring period.

Calculations for the CAT_{Ti} evaluation method using pre-application t_0 measurements

After sample analysis (using the method described in table 11.3), cation content is typically given in mg_{CAT}/L_{sample}. This value must be normalized to the mass of soil used in the digestion to obtain a mass concentration in mg_{CAT}/kg_{soil} or ppm.

The CO_2 sequestration is estimated from the decrease in concentration of mobile weathering material relative to the concentration of the immobile trace elements. The estimation of the decrease in the major cation proxy in the NFZ during the monitoring period is evaluated as follows:

$$F1 = BD_{soil} \times d \times A_{ext} \tag{11.7}$$

$$F2 = Mw_{CO2} / Mw_{CAT} \times n \tag{11.8}$$

$$R_{wm} = CAT_{wm} / TI_{wm} \tag{11.9}$$

$$TI_{ms} = TI_{t1} - TI_{t0} \tag{11.10}$$

$$CAT_{ms} = CAT_{t1} - CAT_{t0} \tag{11.11}$$

$$R_{ms} = CAT_{ms} / TI_{ms} \tag{11.12}$$

$$WR_{t1} = (R_{wm} - R_{ms}) / R_{wm} \tag{11.13}$$

$$\Delta CAT_{application} = WR_{t1} \times TI_{ms} \times R_{wm} \times F1 \times F2 \tag{11.14}$$

$$C_{stored} = \Delta CAT_{application} - \Delta CAT_{prior} \tag{11.15}$$

$$C_{baseline-[field]} = \Delta CAT_{control} = (CAT_{t0} - CAT_{t1})_{control} \times F1 \times F2 \tag{11.16}$$

$$\Delta CAT_{Ti} = \Delta CAT_{application} - \Delta CAT_{control} \tag{11.17}$$

Where:

Variable	Description	Unit
A_{ext}	The field area to which weathering feedstock was applied that is represented by the evaluated sample or set of samples, i.e., the area to which the weathering signal may be extrapolated to, i.e., the area within a homogeneous stratum to which weathering feedstock was applied. Note that therefore the value of A_{ext} will be the same for both C_{stored} (application sites, eq. 11.14) and $C_{baseline-[field]}$ (control sites, eq. 11.16).	m^2
BD_{soil}	Bulk density of soil (measured).	g_{soil}/m^3
d	Sampling depth = the depth the proxy signal is integrated over	m
Mw_{CO2}	Molecular weight of CO_2 = 44.01 g/mol	g_{CO2}/mol
Mw_{CAT}	Molecular weight of the measured cation	g_{CAT}/mol
n	CO_2 sequestration charge capacity of the cation considered ($n = 2$ for Ca and Mg, $n = 1$ for K and Na).	unitless
$F1$	Factor equaling the amount of soil (g_{soil}) in the extrapolation area (A_{ext}) taking into account the depth over which the sample integrated (d); multiplying with this factor therefore extrapolates the weathering signal per gram of soil to the field area this signal represents.	g_{soil}
$F2$	Factor converting the weathering signal in grams cations to a signal in grams CO_2.	g_{CO2}/g_{CAT}
CAT_i	Concentration of the selected major cation proxy at $i = t_0$ or $i = t_1$ i = wm: the cation concentration in the weathering material feedstock i = ms: the cation concentration in the soil at t1, subtracting the baseline t0 concentration	g_{cation} / g_{soil}
TI_i	Concentration of the selected immobile trace elements at $i = t_0$ or $i = t_1$ i = wm: the immobile trace element concentration in the weathering material feedstock i = ms: the immobile trace element concentration in the soil added as part of the feedstock (i.e., at t_1, subtracting the t_0 concentration)	mol/g_{soil}
R_i	Ratio of concentrations of the major cation proxies to the relatively immobile trace elements i = wm: Relative concentrations in the weathering material feedstock i = ms: Relative concentrations in the soil	unitless
WR_i	Estimated weathering rate of the applied soil amendments based on comparing the concentrations of the trace elements and major cations in the soil at the end of the monitoring period, relative to the ratios found in the pre-application feedstock	unitless
$\Delta CAT_{application}$	Gross amount of carbon dioxide stored as carbonate and bicarbonate ions as measured as decrease in the major cation proxy within the NFZ of application sites (weathering signal) over the monitoring period, i.e., between t_0 and t_1.	gCO_2

Variable	Description	Unit
$\Delta CAT_{control}$	Amount of carbon dioxide stored as carbonate and bicarbonate ions on control sites as measured as decrease in the major cation proxy within the NFZ of control sites (weathering signal) over the monitoring period, i.e., between t_0 and t_1. Control sites represent the baseline of natural weathering that would have occurred also on application sites in the absence of the ERW activity.	gCO_2
ΔCAT_{prior}	Gross amount of carbon dioxide stored as carbonate and bicarbonate ions claimed during all prior monitoring periods. This value is 0 during the first monitoring period. This value is equal to the $\Delta CAT_{application}$ value from the previous monitoring period.	gCO_2
ΔCAT_{Ti}	Baseline-corrected decrease in the NFZ-concentration of the cation proxy converted to amount of CO_2 removed during the monitoring period as quantified by the CAT_{Ti} approach.	gCO_2

Applicable loss terms

Given that this approach measures the full removal of a proxy cation from the NFZ rather than directly quantifying carbonic acid weathering, additional discounts have to be made for non-carbonic acid dissolution ($Loss_{acid}$) and cation uptake into plant biomass ($Loss_{plant}$, rule 6.3.5). The loss pathways $Loss_{adsorb}$, $Loss_{carbonate}$, and $Loss_{silicate}$ are implicitly accounted for by this approach if soil samples integrate over the entire depth of the NFZ and are fully digested, but need to be corrected for if only part of the vertical extent of the NFZ is sampled. The FFZ loss terms $Loss_{rivers}$ and $Loss_{rivers}$ need to be accounted for.

11.3.2. The CO_2 Removal Supplier may use CAT_{Ti} type measurements to quantify C_{stored} taking into account the approach-combination constraints in rule 9.5.2. This may be done by following the evaluation method according to eqs. 11.7-11.17. Alternative ways of accounting for the t_0-baseline by taking the t_0 samples just after feedstock applications may also be permissible but require a different set of equations not specified in this methodology.

Subsequent monitoring periods

11.3.3. In order to monitor the same area over multiple monitoring periods, including subsequent deployments of weathering materials, using the CAT_{Ti} type quantification approach following eqs. 11.7-11.17, the initial pre-application t_0 values shall be used. All prior C_{stored} values in the field area shall be subtracted from the C_{stored} values for the current monitoring period.

Approach 3 - $CAT_{porewater}$

In this approach the accumulated cations are measured from soil water samples (see section 11.6) taken at the base of the NFZ using analytical instruments like ICP-MS or ICP-OES (table 11.3).

Similar to approach 1 (CAT_{WM}), C_{stored} can be calculated individually for the different cation proxies (Ca^{2+}, Mg^{2+}, K^+, and Na^+), but the inclusion of several cations in the total C_{stored} quantification should be justified by site-specific context and supporting data.

Calculations

CO_2 sequestration is estimated from the concentration of the selected cation proxy in soil water that has accumulated in the sampling container (i.e., in the process of leaching from the NFZ) during a monitoring period in application and control sites as follows:

$$F3 = (RF - ET - RO)/V_{sample} \times A_{ext} \tag{11.18}$$

$$C_{stored} = \Delta CAT_{application} = \sum CAT_{application} \times F3 \times F2 \tag{11.19}$$

$$C_{baseline-[field]} = \Delta CAT_{control} = \sum CAT_{control} \times F3 \times F2 \tag{11.20}$$

$$\Delta CAT_{porewater} = \Delta CAT_{application} - \Delta CAT_{control} \tag{11.21}$$

Where:

Variable	Description	Unit
A_{ext}	See eq. 11.2	m^2
RF	Volume of precipitation received per area of field. See also information box 1.	L/m^2
ET	Evapotranspiration per area of field. See also information box 1.	L_r/m^2
RO	Runoff estimate per area of field. See also information box 1.	L/m^2
V_{sample}	Soil water sample volume	m^3
Mw_{CO2}	See eq. 11.3	g_{CO2}/mol
Mw_{CAT}	See eq. 11.3	g_{CAT}/mol
n	See eq. 11.3	unitless
$F3$	Factor relating the net volume of water per area of field received from precipitation (corrected for evaporation and runoff) and the volume of soil water captured by the sampling devices to the area of field that the sample (or set of samples) represents; multiplying with this factor therefore extrapolates the weathering signal per volume of soil water to the field area this signal represents, treating the volume of soil water captured as representative of the (likely larger) volume of water that has in fact passed through the soil during the monitoring period.	unitless
$F2$	Factor converting the signal in grams cations to a signal in grams CO_2. See eq. 11.3.	g_{CO2}/g_{CAT}
$\sum CAT_i$	Concentration of the cation proxy in the combined soil water that has accumulated over the monitoring period (at i = *control site* or *application site*), i.e., between t_0 and t_1. Note that water accumulated in soil sampling devices can and should be sampled more than once during a monitoring period.	g_{CAT}
$\Delta CAT_{application}$	Gross amount of carbon dioxide stored as carbonate and bicarbonate ions as measured as export of the major cation proxy from the NFZ of application sites (weathering signal) over the monitoring period, i.e., between t_0 and t_1.	gCO_2

Variable	Description	Unit
$\Delta CAT_{control}$	Amount of carbon dioxide stored as carbonate and bicarbonate ions on control sites as measured as export of the major cation proxy from the NFZ of control sites (weathering signal) over the monitoring period, i.e., between t_0 and t_1. Control sites represent the baseline of natural weathering that would have occurred also on application sites in the absence of the ERW activity.	gCO_2
$\Delta CAT_{porewater}$	Baseline-corrected decrease in the NFZ-concentration of the cation proxy converted to amount of CO_2 removed during the monitoring period as quantified by the $CAT_{porewater}$ approach.	gCO_2

Information box 1

> **REMARK ON HOW TO ESTIMATE THE WATER VOLUME INFILTRATING THE SOIL OVER A GIVEN PERIOD OF TIME:** We call this parameter soil water flux (F_{sw}) and measure it in units of volume of water per area field and time (L m^{-2} yr^{-1}). To calculate it, we need an estimate of the following components: Rainfall, Evapotranspiration, and Runoff. Rainfall (RF) is usually measured using a rain gauge and expressed in units of millimetres (mm) of height or depth. To convert these dimensions to volume of water per collection area 1 mm of precipitation equals 1 L/m^2. Evapotranspiration (ET) is typically measured in millimetres of water (i.e. volume of water moved per unit area of the Earth's surface) in a set unit of time, where, again, 1 mm converts to 1 L/m^2. Finally, runoff (RO) of precipitation describes water that precipitates above a given field area but does not soak into the soil and instead is lost to the given area because it flows across its surface. It is again measured in mm that can be 1:1 converted to units of L/m^2. Runoff can be determined using the runoff curve number (CN) developed by the USDA Natural Resources Conservation Service, an empirical parameter used in hydrology for predicting direct runoff or infiltration from rainfall excess. Finally, we can calculate F_{sw} as follows: $F_{sw} = RF - ET - RO$.

Applicable loss terms

The loss pathway non-carbonic acid weathering ($Loss_{acid}$) needs to be corrected for. The loss pathways $Loss_{plant}$, $Loss_{adsorb}$, $Loss_{carbonate}$, and $Loss_{silicate}$ are implicitly accounted for by this approach if soil water is sampled at the base of the NFZ but need to be corrected for if samples are collected at shallower depth. The FFZ loss terms $Loss_{rivers}$ and $Loss_{rivers}$ need to be accounted for.

11.3.4. The CO_2 Removal Supplier may use $CAT_{porewater}$ type measurements to quantify C_{stored} according to eqs. 11.2, 11.18-11.21 and taking into account the approach-combination constraints in rule 9.5.2.

Approach 4 - $BIC_{porewater}$

In the $BIC_{porewater}$ approach, accumulated bicarbonate and carbonate ions, the primary dissolved products of carbonic-acid weathering, are measured in soil water samples (see section 10.6) taken at the base of the NFZ. Two chemical proxies can be used for this approach: total alkalinity (TA) and dissolved inorganic carbon (DIC). Each method provides different insights and has distinct limitations (Mills et al., 2024).

TA measures a solution’s capacity to neutralize acid and is defined as the excess of proton acceptors (e.g., HCO_3^-, CO_3^{2-}, OH^-) over proton donors (H^+).

$$TA = [HCO_3^-] + 2[CO_3^{2-}] + [B(OH)_4^-] + [OH^-] - [H^+] + (any\ other\ relevant\ ions) \qquad (11.22)$$

As illustrated in eq. 11.22, TA increases with the release of bicarbonate ions during silicate weathering. TA is relatively stable across environmental conditions, making it a more robust indicator of long-term carbon sequestration. However, TA also has drawbacks as a proxy for CDR in soils. While reliable in carbonate-buffered systems like seawater, TA measurements in soil porewater are complicated by non-carbonate acid-base species, such as organic acids, phosphates, and ammonia, which contribute to alkalinity without reflecting atmospheric CO_2 removal (Bijma et al., 2025). Thus, interpreting TA as a proxy for CDR in soils requires caution and context-specific calibration.

DIC is the total amount of inorganic carbon species in solution, hence the sum of $CO_{2\ (aq)}$, HCO_3^-, and CO_3^{2-}:

$$DIC = [CO_{2\,(aq)}] + [HCO_3^-] + [CO_3^{2-}] \qquad (11.23)$$

DIC is not conserved under open-system conditions. It varies with pH, temperature, and CO_2 partial pressure (pCO_2). For example, if soil warms or acidifies, $CO_2(aq)$ can degas into the atmosphere, reducing DIC without reversing the weathering reaction. TA, by contrast, remains stable in this case, as proton balances shift without a net loss of alkalinity. Still, neither DIC nor TA alone provides a complete picture of carbon removal; both must be interpreted alongside system boundaries, CO_2 sources, and geochemical context.

Approach 4a - BIC$_{porewater}$ (Total alkalinity - TA)

For total alkalinity measurement of a water sample, a known volume of the sample is titrated with a standardized strong acid, typically 0.02–0.1 N HCl or H_2SO_4, while monitoring the pH. The titration proceeds until the solution reaches a pH of approximately 4.5, at which point all carbonate species, primarily bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}), are protonated to carbonic acid (H_2CO_3), which rapidly decomposes into $CO_2(aq)$ and water. This $CO_2(aq)$ is rapidly degassed from the solution, especially if the sample is stirred or exposed to air, effectively removing the carbonate species as gas.

Given that TA is a measure of the total buffering capacity of a solution, it accounts for all titratable bases (i.e., proton acceptors). Thus, other weak acid/base conjugates besides bicarbonate and carbonate present in soil waters can contribute to TA (table 11.3). The volume of acid added during titration corresponds to the number of equivalents of base neutralized, allowing calculation of TA in e.g. micromoles per liter (µmol/L). To accurately measure CO_2 sequestration using total alkalinity, the contribution of other weak acid/base conjugates has to be identified, quantified, and either corrected for or excluded to isolate the alkalinity specifically derived from carbonic acid weathering (Kerr et al., 2023; Song et al., 2023). Additionally, the pH needs to be measured and a geochemical modeling software (e.g., PHREEQC) used in order to assess the relative contributions of HCO_3^- and CO_3^{2-} to alkalinity.

Table 10.6. Key weak acid/base conjugates that can contribute to total alkalinity (TA) at pH ranges relevant for soils.

Species	Conjugate base form	pKa (approximately)	Relevant pH Range
Bicarbonate	HCO_3^-	6.3	5.5 – 8.5
Carbonate	CO_3^{2-}	10.3	> 9.5
Fulvic and humic acids	$R\text{-}COO^- / R\text{-}O^-$	4 – 7	5 – 8
Dihydrogen Phosphate	$H_2PO_4^-$	2.15	< 5
Hydrogen Phosphate	HPO_4^{2-}	7.2	6 – 8.5
Hydrogen sulfide	HS^-	7.0	~6.5 – 8

CO_2 sequestration is estimated from the difference of accumulated bicarbonate species in leachate waters from the NFZ, between the application site(s) and the control site(s), for a selected monitoring period.

Approach 4b - BICporewater (Dissolved inorganic carbon - DIC)

This method quantifies the total concentration of inorganic carbon species in soil water, including aqueous carbon dioxide (CO_2(aq)), bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}). Among these, CO_2(aq) is highly transient under open-system conditions such as near-surface soils, where it can readily degas to the atmosphere. Because of its short residence time and reversibility, CO_2(aq) does not represent durable carbon sequestration and must be excluded from crediting.

To isolate the bicarbonate and carbonate fractions, the measured DIC must be corrected by estimating and removing the CO_2(aq) component. This can be done using carbonate speciation calculations based on measured DIC, pH, and temperature.

Calculations for approaches 4a and 4b

CO_2 sequestration is estimated from the concentration of the accumulated bicarbonate/carbonate proxy in soil water that has accumulated in the sampling container (i.e., in the process of leaching from the NFZ) during a monitoring period in application and control sites as per the equations below. The equations below assume that the analytical data are in units of charge equivalents (unitless, for approach 4a) and grams carbon (g_C, for approach 4b):

$$F4_{ALK} = Mw_{CO2} / n \quad \text{(for approach 4a)} \tag{11.24}$$

$$F4_{DIC} = Mw_{CO2} / Mw_{C} \quad \text{(for approach 4b)} \tag{11.25}$$

$$C_{stored} = \Delta BIC_{application} = \sum BIC_{application} \times F3 \times F4 \tag{11.26}$$

$$C_{baseline-[field]} = \Delta BIC_{control} = \sum BIC_{control} \times F3 \times F4 \tag{11.27}$$

$$\Delta BIC_{porewater} = \Delta BIC_{application} - \Delta BIC_{control} \tag{11.28}$$

Where:

Variable	Description	Unit
Mw_{CO2}	Molecular weight of CO_2 = 44.01 g/mol	g_{CO2}/mol
Mw_C	Molecular weight of carbon = 12.01 g/mol	g_C/mol
F3	Factor relating the net volume of water per area of field received from precipitation (corrected for evaporation and runoff) and the volume of soil water captured by the sampling devices to the area of field that the sample (or set of samples) represents; multiplying with this factor therefore extrapolates the weathering signal per volume of soil water to the field area this signal represents, treating the volume of soil water captured as representative of the (likely larger) volume of water that has in fact passed through the soil during the monitoring period. See eq. 11.18.	unitless
n	*n = 1* if TA is expressed per mole of HCO_3^-, or *n* = 2 if CO_3^{2}– dominates. Determined by pH measurement and geochemical modeling, see above.	unitless
$F4_{ALK}$	Factor converting charge-equivalents (from alkalinity measurements) to grams CO_2 sequestered, assuming that one charge-equivalent can bind one mol of bicarbonate.	g_{CO2}
$F4_{DIC}$	Factor converting grams of inorganic carbon (from DIC measurements) to grams CO_2.	g_{CO2}/g_C
$\sum BIC_i$	Concentration of the (bi)carbonate proxy in the combined soil water that has accumulated over the monitoring period (at *i* = *control site* or *application site*). Note that water accumulated in soil sampling devices can and should be sampled more than once during a monitoring period.	g_C
$\Delta BIC_{application}$	Gross amount of carbon dioxide stored as carbonate and bicarbonate ions measured as export of the (bi)carbonate proxy from the NFZ of application sites (weathering signal) over the monitoring period, i.e., between t_0 and t_1.	gCO_2
$\Delta BIC_{control}$	Amount of carbon dioxide stored as carbonate and bicarbonate ions on control sites as measured as export of the major cation proxy from the NFZ of control sites (weathering signal) over the monitoring period, i.e., between t_0 and t_1. Control sites represent the baseline of natural weathering that would have occurred also on application sites in the absence of the ERW activity.	gCO_2
$\Delta BIC_{porewater}$	Baseline-corrected decrease in the NFZ-concentration of the (bi)carbonate proxy converted to amount of CO_2 removed during the monitoring period as quantified by the $BIC_{porewater}$ approach.	gCO_2

Applicable loss terms

The loss pathways $Loss_{plant}$, $Loss_{adsorb}$, $Loss_{carbonate}$, $Loss_{acid}$, and $Loss_{silicate}$ are implicitly accounted for by this approach if soil water is sampled at the base of the NFZ but need to be corrected for if shallower depths are sampled. The FFZ loss terms $Loss_{rivers}$ and $Loss_{rivers}$ need to be accounted for.

11.3.5. The CO_2 Removal Supplier may use $BIC_{porewater}$ type measurements to quantify C_{stored} according to eq. 11.18, 11.24-11.28 and taking into account the approach-combination constraints in rule 9.5.2.

Approach 5 - CAT_{resin}

Ion exchange resins (polymer beads widely used in environmental monitoring) work by adsorbing cations (positively charged ions) from the surrounding soil solution in a process similar to how roots or clay particles retain nutrients. When a cation exchange resin is placed in soil, it does not directly attract cations from solid soil particles. Instead, the cations must be dissolved in soil pore water to be adsorbed by the resin. The negatively charged functional groups on the resin attract and bind cations from the water. As cations bind to the resin, it releases an equivalent charge of counterions (H^+ or Na^+) to maintain charge balance.

Cation exchange resins can capture Ca^{2+}, Mg^{2+}, K^+, Na^+, Al^{3+}, Fe^{3+}, and other positively charged ions. Within cation exchange resins, sulfonic acid ($-SO_3^-$) resins are strong and work in a broad pH range, phosphonic ($-PO_3H^-$) resins are specialized for metal ion binding, and carboxyl ($-COO^-$) resins are weak-acid based and typically lose efficiency at low pH values (<4-5). Strong acid resins work effectively across a wide pH range (typically pH 1–14), but recent studies (Power et al., 2025; Santos et al., 2024) have shown that they can dissolve portions of the ERW rock powders artificially inflating cation measurements. Thus, weak acid resins might be more appropriate for C_{stored} quantification, but there are currently (September 2025) no peer-reviewed studies that have specifically employed weak acid cation exchange resins to measure cation fluxes in ERW settings.

Given that resins provide a cumulative quantification of cation adsorption, CO_2 sequestration is estimated from the cation changes in the NFZ within a monitoring period lasting from t_0 to t_1 as follows:

$$C_{stored} = \Delta CAT_{application} = CAT_{application} / A_{resin} \times F2 \times A_{ext} \tag{11.29}$$

$$C_{baseline[field]} = \Delta CAT_{control} = CAT_{control} / A_{resin} \times F2 \times A_{ext} \tag{11.30}$$

$$\Delta CAT_{resin} = \Delta CAT_{application} - \Delta CAT_{control} \tag{11.31}$$

Where:

Variable	Description	Unit
A_{ext}	The field area to which weathering feedstock was applied that is represented by a given site sampled by the sensor, i.e., the area to which the weathering signal may be extrapolated to, i.e., the area within a homogeneous stratum to which weathering feedstock was applied. Note that therefore the value of A_{ext} will be the same for both C_{stored} (application sites, eq. 11.29) and $C_{baseline-[field]}$ (control sites, eq. 11.30).	m^2
A_{resin}	The surface area of the part of the sensor (i.e., membrane) that is in contact with and can interchange ions with the surrounding soil water.	m^2
Mw_{CO2}	Molecular weight of CO_2 = 44.01 g/mol	g_{CO2}/mol
Mw_{CAT}	Molecular weight of the measured cation	g_{CAT}/mol
n	CO_2 sequestration charge capacity of the cation considered (n = 2 for Ca and Mg, n = 1 for K and Na).	unitless
$F2$	Factor converting the weathering signal in grams cations to a signal in grams CO_2. See eq. 11.3	g_{CO2}/g_{CAT}

Variable	Description	Unit
CAT_i	Amount of the selected major cation proxy collected by the resin throughout the monitoring period in *i = application site* or *i = control site.*	g_{cation}
$\Delta CAT_{application}$	Gross amount of carbon dioxide stored as carbonate and bicarbonate ions as measured as export of the major cation proxy from the NFZ of application sites (weathering signal) over the monitoring period, i.e., between t_0 and t_1.	gCO_2
$\Delta CAT_{control}$	Amount of carbon dioxide stored as carbonate and bicarbonate ions on control sites as measured as export of the major cation proxy from the NFZ of control sites (weathering signal) over the monitoring period, i.e., between t_0 and t_1. Control sites represent the baseline of natural weathering that would have occurred also on application sites in the absence of the ERW activity.	gCO_2
ΔCAT_{resin}	Baseline-corrected decrease in the NFZ-concentration of the cation proxy converted to amount of CO_2 removed during the monitoring period as quantified by the $CAT_{porewater}$ approach.	gCO_2

Applicable loss terms

The loss pathway non-carbonic acid weathering ($Loss_{acid}$) needs to be corrected for, except if the CO_2 removal supplier can demonstrate that the utilized resins do not react with non-carbonic acid weathering derived cations. The loss pathways $Loss_{plant}$, $Loss_{adsorb}$, and $Loss_{silicate}$ are implicitly accounted for by this approach if the sensor tip reaches the base of the NFZ but losses occurring between NFZ depth and sensor tip depth need to be corrected for if sensor tip is shallower. The FFZ loss terms $Loss_{rivers}$ and $Loss_{rivers}$ need to be accounted for.

Limitations of this approach

One limitation of this approach is that the resin may not capture all the cations present in the sampled soil volume. Another limitation could arise from the influence of water movement on the efficiency of cation exchange. If soil is too dry, few cations are in solution, leading to lower adsorption by the resin. If soil is too wet (saturated), the resin might capture more cations, but excessive water movement (leaching) could wash away some mobile ions before adsorption. To understand the overall efficiency of the resin, the accuracy of the resin is recommended to be calibrated for the specific soil texture class (i.e., sand, silt, clay content) and proxy cation. Moreover, estimations of the effective contact area calibration of resins for hydrology of the resin should be included in the monitoring plan for reducing uncertainty of results.

Because of the discussed limitations and the lack of scientific studies demonstrating the effectiveness of this approach for CDR quantification in ERW, the CAT_{resin} approach may only be used as a validation method under this methodology.

11.3.6. The CO_2 Removal Supplier may use CAT_{resin} type measurements to validate C_{stored} according to eqs. 11.29-11.31 and taking into account the approach-combination constraints in rule 9.5.2. In the context of the CAT_{resin} approach, the sampling depth shall be the deepest depth reached by the sensor membrane.

Approach 6 - SIC_{soil}

As discussed in section 1.6, the products of silicate feedstock weathering can re-precipitate in the form of solid carbonates under certain conditions. Such secondary carbonate mineral formation could be viewed as a loss term due to the production of 1 mol CO_2 previously sequestered as bicarbonate as a result of silicate feedstock weathering per mol of formed $CaCO_3$ (eq. 1.4) as well as the danger of future dissolution of such carbonates by non-carbonic acids, which would release another mol of CO_2 per mol $CaCO_3$. However, under the reasonable assumption that soil conducive to producing pedogenic carbonates is unlikely to change its conditions (specifically changing from high pH to low pH) even on long time scales so drastically that carbonates within it start to net-dissolve, secondary (pedogenic) carbonates can be regarded as safely stored carbon (C_{stored}) if they are accounted for as 1 mol CO_2 stored per 1 mol $CaCO_3$ formed (see eq. 1.4). Additionally, this methodology only allows crediting on the basis of secondary carbonate formation only in soils with natural pH levels ≥6.5 (see rule 11.3.7a), where carbonate dissolution by non-carbonic acid weathering is negligible (Dietzen & Rosing, 2023).

The main and direct approach for quantifying C_{stored} as $CaCO_3$ is measuring soil inorganic carbon (SIC) concentrations using one of the methods described in table 11.3. Excess SIC resulting from the ERW activity can be estimated by measuring SIC increase over the duration of a monitoring period (i.e., from t_0 until t_1) in application sites relative to associated control sites (eqs. 11.32-11.35).

In addition to quantification by SIC measurements, new $CaCO_3$ formation as a consequence of ERW activity can be validated using isotope measurements. More negative ("lighter") stable isotope signatures of carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) would be expected in $CaCO_3$ formed from atmospheric CO_2 compared to lithogenic (geological origin) carbonates (Dietzel et al., 1992; Krishnamurthy et al., 2003; Washbourne et al., 2015). Percentage share of lithogenic vs pedogenic carbonates in soil samples can be estimated on the basis of such data following assumptions and methods described by Washbourne et al. (2015). Thus, a statistically significant shift toward higher pedogenic carbonate content (i.e., more negative $\delta^{13}C$ and $\delta^{18}O$ values) would clearly validate a formation of secondary carbonates as a result of the ERW activity. However, in cases where the ERW activity adds secondary carbonate minerals to a background of soil dominated already by pedogenic carbonates, such a shift might not be clearly distinguishable between control and application sites or between t_0 and t_1 within application sites, due to an existing background of low stable isotope signatures. In such cases, the stable isotope approach could still be used to validate the additional carbonates quantified by SIC concentration measurements if it can be demonstrated that the absolute $\delta^{13}C$ and $\delta^{18}O$ values are on the low end of the range reported in figure 3 of Washbourne et al. (2015), i.e., $\delta^{13}C$ (PDB) <~-20‰ and $\delta^{18}O$ (PDB) <~-15‰ in both t_0 and t_1 of the application site samples as well as in the control site samples.

Alternatively or in addition to stable isotope analyses, radiocarbon (^{14}C) dating can distinguish modern soil carbonates from lithogenic ones. Due to atmospheric variation in radiocarbon levels, this method can in principle resolve the age of modern soil carbonates with a resolution of decades. This could make it a useful addition to stable isotope measurements in validating that carbonates have been added to soil as a consequence of the ERW activity by demonstrating significant content of modern carbonate in the soil sample (Washbourne et al., 2015). As for the stable isotope approach described above, the effect may only be distinguishable compared to a background of soil dominated by geological carbonate but the combination of the two approaches may still strengthen evidence for validating significant pedogenic carbonate formation.

The CO_2 sequestration is quantified from an increase in soil inorganic carbon (SIC) over a monitoring period from the time just after feedstock application (t_0) to the end of the monitoring period (t_1):

$$F5 \;=\; Mw_{CO2} \,/\, Mw_{C} \times n \qquad (11.32)$$

$$C_{stored} \;=\; \Delta SIC_{application} \;=\; (\,SIC_{t1} \,-\, SIC_{t0})_{application} \;\times\; F1 \;\times\; F5 \qquad (11.33)$$

$$C_{baseline-[field]} \;=\; \Delta SIC_{control} \;=\; (\,SIC_{t1} \,-\, SIC_{t0})_{control} \times\; F1 \;\times\; F5 \qquad (11.34)$$

$$\Delta SIC_{WM} \;=\; \Delta SIC_{application} \,-\, max(0,\, \Delta SIC_{control}) \qquad (11.35)$$

Note that in eq. 11.35, if the value of $\Delta SIC_{control}$ is negative, it has to be replaced by zero. The reason is that it is not possible to determine whether this control-site SIC loss was due to carbonate weathering by carbonic acid (implying CDR by bicarbonate formation) or non-carbonic acids (implying CO_2 formation/emissions, eq. 1.4). Therefore, setting $\Delta SIC_{control} = 0$ is the conservative assumption in this case.

Where:

Variable	Description	Unit
A_{ext}	The field area to which weathering feedstock was applied that is represented by the evaluated sample or set of samples, i.e., the area to which the weathering signal may be extrapolated to, i.e., the area within a homogeneous stratum to which weathering feedstock was applied. Note that therefore the value of A_{ext} will be the same for both C_{stored} (application sites) and $C_{baseline-[field]}$ (control sites).	m^2
BD_{soil}	Bulk density of soil (measured).	g_{soil}/m^3
d	Sampling depth = the depth the proxy signal is integrated over	m
Mw_{CO2}	Molecular weight of CO_2 = 44.01 g/mol	g_{CO2}/mol
Mw_{C}	Molecular weight of carbon (12.01 g/mol). Note that if the measurement output (e.g., from calcimetry) provides the concentration of $CaCO_3$ rather than carbon, the $CaCO_3$ concentration first needs to be converted to carbon concentration.	g_C/mol
n	Stoichiometric factor reflecting the carbon sequestration capacity in mol CO_2 per mol of formed $CaCO_3$: n =1, see eq. 1.4.	unitless
$F1$	Factor equaling the amount of soil (g_{soil}) in the extrapolation area (A_{ext}) taking into account the depth over which the sample integrated (d); multiplying with this factor therefore extrapolates the weathering signal per gram of soil to the field area this signal represents. See eq. 11.2.	g_{soil}
$F5$	Factor converting the signal in grams of carbon to a signal in grams of CO_2.	g_{CO2}/g_C
SIC_i	SIC concentration at $i = t_0$ or $i = t_1$. Note that SIC_{t0} is sampled after feedstock application to correct for any carbonate component contained in the feedstock.	g_c / g_{soil}

Variable	Description	Unit
$\Delta SIC_{application}$	Gross amount of carbon dioxide stored as carbonate mineral as measured as SIC concentration increase within the NFZ of application sites (weathering signal).	gCO_2
$\Delta SIC_{control}$	Amount of carbon dioxide stored as carbonate mineral on control sites as measured as SIC concentration increase within the NFZ of control sites, representing the baseline carbonate mineral formation that would have occurred also on application sites in the absence of the ERW activity.	gCO_2
ΔSIC_{WM}	Baseline-corrected increase in precipitated carbonate minerals (measured as SIC) during the monitoring period as quantified by the SIC_{WM} approach and converted to amount of CO_2 removed .	gCO_2

Applicable loss terms

Given that the measurement directly reflects the sequestered carbon from CO_2, no NFZ loss terms apply to this quantification type. The FFZ loss terms $Loss_{rivers}$ and $Loss_{rivers}$ need to be accounted for.

11.3.7. The CO_2 Removal Supplier may use the SIC_{soil} approach, i.e., using SIC concentration measurements to quantify C_{stored} as $CaCO_3$ within the NFZ according to eqs. 11.32-11.35 under the conditions described in subrules a-f:

a. SIC_{soil} shall only be eligible in soils with pH levels of at least pH 6.5 (Dietzen & Rosing, 2023) prior to the first feedstock application of a given Crediting Period (as determined by pre-application soil characterization, see rule 9.4.4.

b. Significantly elevated SIC concentrations shall only be interpreted as a signal for C_{stored} as $CaCO_3$ and used as the basis for its quantification if the following conditions are met:

- Successful validation by an isotope-based approach (subrules c-d).
- SIC increase between t_0 and t_1 measured in application site samples is both statistically significant and larger than any such increase measured in corresponding control site samples.
- Time point t_0 samples shall be collected after feedstock application. This ensures that the subtraction of SIC_{t0} from SIC_{t1} inherently corrects for any carbonates contained in the carbonate feedstock added to the application sites. If t_0 samples are collected before feedstock application, results must be corrected for feedstock carbonate-content measured by dry combustion (table 3.1).

c. In order to validate the interpretation of C_{stored} as $CaCO_3$ on the basis of SIC concentration measurements (subrule b), the CO_2 Removal Supplier shall additionally use measurements of carbon and oxygen stable isotopes in carbonates from a subset of representative soil samples to demonstrate the atmospheric carbon content of the additionally formed carbonates. This validation shall be fulfilled by demonstrating a statistically significant shift toward more negative $\delta^{13}C$ and $\delta^{18}O$ values between t_0 and t_1 on application sites that is also statistically significantly larger than any such shifts observed at corresponding control sites. Conceptually, such a shift will occur from the specific $\delta^{13}C$ and $\delta^{18}O$ values found in the soil after feedstock application (t_0) toward the conceptual end members at $\delta^{13}C$ (PDB) <~-20‰ and $\delta^{18}O$ (PDB) <~-15‰ (Washbourne et al., 2015).

d. Alternatively or in addition to stable isotope measurements, the CO_2 Removal Supplier may use radiocarbon (^{14}C) analyses from a subset of representative soil samples to validate the signal for C_{stored} as $CaCO_3$ by determining the age of the soil inorganic carbon. Significantly reduced soil carbonate age between application site t_0 and t_1 samples that is also statistically significantly larger than any such age decrease observed in corresponding control sites may validate C_{stored} as $CaCO_3$ quantified as per subrule b.

e. If the C_{stored} as $CaCO_3$ can be properly quantified and validated in accordance with subrules b-d, this C_{stored} value may be added to the CORC quantification either independently (as the only way of quantifying C_{stored} during a given monitoring period) or in addition to C_{stored} quantified on the basis of one of the other eligible approaches (rule 9.5.2) as long as subrule f is followed.

f. If C_{stored} as bicarbonate, alkalinity, or cations exported from the NFZ (i.e., via one of the other eligible quantification approaches in table 11.3) is quantified in the same monitoring period or a monitoring period after C_{stored} is quantified as $CaCO_3$, SIC concentrations shall be measured in parallel to each measurement quantifying C_{stored} as bicarbonate/alkalinity/cations exported from the NFZ. Bicarbonate/alkalinity/cation export must be corrected for (i.e., discounted by) any decrease in SIC observed between measurement time points. For example, for 1 mol of SIC decrease between two measurement time points, C_{stored} (from bicarbonate/cation export) needs to be corrected for (i.e., decreased by) 1 mol bicarbonate or 1 charge-equivalent cation or alkalinity.

12. ERW simulation models

12.1. Guidelines for ERW models

Enhanced Rock Weathering is an inherently slow process that can have a project duration of several years or decades and quantification of the term C_{stored} is associated with large uncertainties. The combination of models[99] and measurements could provide a pathway to decrease these uncertainties without increasing the sampling density. Therefore, this methodology encourages CO_2 Removal Suppliers to undertake site-specific modeling of their ERW activity in addition to quantification by experimental monitoring. Such efforts can serve extrapolation of C_{stored} quantified by measurements to reduce the necessary sampling density.

Modeling ERW implies the accounting for a wide range of geochemical, physical, and biological parameters and processes. Various modeling approaches of different types have been suggested in the literature (table 12.1) but to date (Oct 2025), no scientific consensus exists on the best approach to simulate the enhanced weathering process (Kanzaki et al., 2025). As different models can vary significantly with respect to the data required, inputs, outputs, and theoretical approaches, one purpose of this section is to set guidelines to steer the simulation process towards reliable results. It is important to note that this section 12 discusses process-based models simulating relevant (bio)geochemical, hydrological, physical, and biological processes of ERW in the soil, as opposed to statistical models, process-based models simulating carbon losses in the FFZ (surface-waters and the ocean, see section 6.2), or simple sets of calculations. Thus, the output of these models pertains mostly to C_{stored} and some models may also have the capacity to quantify NFZ based losses (C_{loss}), i.e., $Loss_{acid}$, $Loss_{plant}$, $Loss_{adsorb}$, and/or $Loss_{silicate}$.

Table 12.1 provides an overview of available models for ERW that are published as part of peer-reviewed studies. At this time, SCEPTER, SMEW, and KELLAND may be seen as among the more widely used models. Differences between these models could provide reasons to prefer one over the other depending on specific conditions. SCEPTER and KELLAND are one-dimensional (1D) reactive-transport models, simulating geochemical, biological, and physical processes across a vertical gradient as well as time. By contrast, the coupled ecohydrology-biogeochemistry model SMEW has no depth dimension, assuming that all relevant processes occur in a well-mixed upper soil layer (Bertagni et al., 2024; Cipolla et al., 2021a, 2021b) but it features a dynamic soil moisture regime that captures cation accumulation and flushing dynamics relevant to validate against monitoring measurements. SCEPTER (unlike KELLAND) contains functions that simulate tillage and other types of soil mixing. It can also trace soil organic matter and integrate climatic variables (temperature, water). However, the current version 1.0 of SCEPTER (Kanzaki et al., 2024) can simulate neither plant uptake of cations and nutrients nor secretion of organics, whereas the other two models can simulate biologically mediated cation and carbon fluxes. Finally, the KELLAND model seems best equipped among the three to simulate the effect of nitrogen fertilizers on ERW.

---

[99] In this methodology the words ‘model’, ‘simulation’, etc. are to be understood in a wide sense including not only the equations and/or computer programs they are composed of, but also the subsequent data analysis and interpretation of the results by experts.

An ERW model usually provides several outputs from which an estimate of the amount of carbon stored is determined. Simulated estimates require validation via in-situ measurements to determine the accuracy of the simulation in predicting weathering behavior over time. Model validation is based on comparing the measurements of a weathering signal and the result predicted by the simulation, and depending on specifics of the selected approach, several different quantities can be measured for validation purposes (see section 11.2).

Table 12.1. Examples of published models for quantifying CDR in Enhanced Rock Weathering.

Model name/ reference	Model type	Simulated processes
Kelland (Kelland et al., 2020; A. L. Lewis et al., 2021; Vienne et al., 2022)	PHREEQC- based 1D reactive transport model	● Vertical fluid and dissolved ion transport through soil column ● Silicate mineral weathering rates: mineral dissolution and (secondary) precipitation ● CO_2 equilibration and carbonate chemistry ● Effect of nitrogen fertilizers ● Effect of respiration and plant uptake on cation and carbon balance ● Cation sorption/exchange
SMEW (Bertagni et al., 2024; Cipolla et al., 2021a, 2021b)	Coupled ecohydrology-biogeochemistry model	● Soil moisture dynamics (informed by rainfall, evaporation, and transpiration, leakage) ● Silicate mineral weathering rates: mineral dissolution and (secondary) precipitation ● CO_2 equilibration and carbonate chemistry ● Biological (degradation, respiration, plant uptake) carbon cycling ● Dissolved mineral (silicate, cation) fluxes ● Cation sorption/exchange
SCEPTER (Kanzaki et al., 2022; Baek et al., 2023; Kanzaki et al., 2024)	1D reactive transport model	● Vertical fluid and dissolved ion transport through soil column ● Silicate mineral weathering rates: mineral dissolution and (secondary) precipitation ● CO_2 equilibration and carbonate chemistry ● Soil mixing (by organisms or tillage) ● Grain-size driven changes in feedstock surface area as weathering proceeds ● CO_2 introduction into the soil profile through gas phase transport and organic carbon respiration ● Cation sorption/exchange
TOUGHREACT (Deng et al., 2023; Xu et al., 2011)	1D reactive transport model based on THOUGHREACT	● Vertical fluid and dissolved ion transport through soil column ● Silicate mineral weathering ● Microbial degradation of organic matter ● Cation exchange ● Kinetic mineral reactions
(Beerling et al., 2020)	1D reactive transport model	● Vertical fluid and dissolved ion transport through soil column ● Silicate mineral weathering ● Carbonate speciation including secondary carbonate formation ● Influence of crop productivity
(Kantzas et al., 2022)	1D reactive transport model coupled to climate model	● Vertical fluid and dissolved ion transport through soil column ● Silicate mineral weathering ● Effect of nitrogen fertilizer application ● (effects of different climate scenarios)

12.2. Requirements for process-based ERW models

12.2.1. The CO_2 Removal Supplier may use process-based models to simulate the ERW process as an additional means to quantifying C_{stored}. Results from such models may be used for site-specific extrapolation (see subrule e) of data from empirical measurements using a quantification method (rule 9.5.2), provided that subrules a-k are met. While empirical measurements shall be the principle way of quantifying and validating C_{stored}, supplementing empirical data with modeling results can reduce the required sampling density and/or frequency while achieving statistical significance (i.e. reduce uncertainty, section 10.2).

a. **Eligible model types** for process-based simulation of the ERW process and quantification of C_{stored} shall have the following attributes:

   i. Based on peer-reviewed models that are based on commonly accepted scientific concepts and theoretical background;

   ii. The model shall be specifically designed for soil science applications suitable for quantifying CDR based on ERW (including but not limited to those in table 12.1);

   iii. The parameterization (e.g. solubility, kinetic and thermodynamic data) shall be based on measurements reflecting conditions relevant to in-field applications as much as possible;

   iv. The modeling approach shall be based on data-driven mechanistic functions (i.e., process-based) that take into account the relevant physico-biogeochemical processes of ERW (i.e., interactions between mineral, soil, biological organism, water, atmosphere, and meteorological drivers) rather than based fully on statistical predictions of empirical data;

   v. Non-eligible models in this context of quantifying C_{stored} include entirely statistical models, models that do not take into account the specific biogeochemical processes of weathering, and simplistic models (e.g., restricted to first-order kinetics, collection of budget-type equations, etc.);

   vi. While the choice is not restricted to them, the models described as KELLAND, SMEW, and SCEPTER models above and in table 11.1 provide examples of generally eligible model types.

b. **Input and project specificity**: the input data for the model shall be based on site- and project-specific parameters from empirical measurements, including soil-physical and biogeochemical properties (e.g., those listed in table 9.2) of the relevant homogeneous stratum (see subrule e), properties of the utilized feedstock rock (e.g., mineralogical composition, specific surface area, particle size distribution, see rule 3.6.2), and the local climate (e.g., rainfall, air temperature). As new data become available on these parameters (e.g., based on results of the in-field monitoring and measurement activities conducted by the CO_2 Removal Supplier), the model shall be updated at the next appropriate juncture, e.g., for the next monitoring period. Site- and project specific data may be supplemented as necessary by values obtained from peer-reviewed scientific literature or relevant scientific datasets (e.g., soil maps, data from meteorological stations, etc.).

c. **Modelled phenomena**: the model shall at least simulate the following aspects of ERW:

   i. The most relevant biogeochemical processes occurring in the system, (including feedstock mineral dissolution and secondary mineral precipitation, CO_2 equilibration and carbonate chemistry, cation sorption and exchange, biological respiration) modeled on the basis of scientifically relevant thermodynamic and kinetic coefficients related to the reactions. Modeling of feedstock weathering (mineral dissolution) shall include the effects of the physical size of the mineral particles being spread (e.g. grain size, surface area, roughness, and changes to particle size due to mineral dissolution);

   ii. The influence of key environmental parameters (e.g., moisture, pH, temperature, ion concentrations, etc.) on the modeled biogeochemical processes;

   iii. Soil moisture dynamics and/or the transport of fluids and chemical species through the soil system.

   Additionally, the model *should* simulate the following aspects of ERW:

   iv. Secondary effects affecting the dissolution of grains such as fluid supersaturation and surface passivation effects;

   v. Soil disturbances, e.g., due to tillage or bioturbation;

   vi. Plant cation uptake;

   vii. Non-carbonic acid weathering and the effect of (nitrogen) fertilizer;

   viii. Grain-size driven changes in feedstock surface area as weathering proceeds;

   ix. Soil moisture dynamics;

   x. Soil organic carbon stocks.

d. **Model output**: The site-specific process-based model shall provide at least an estimation of the expected weathering and the associated CO_2 removal (in tCO_2e) as a function of time (i.e. year-to-year) over the monitoring period and the duration of the project (project time horizon). The model should also be able to output other supporting data, such as concentrations of the relevant chemical species, element mass transfer rates, weathering rates, soil organic carbon dynamics, rates of losses to plants, secondary mineral formation, cation adsorption, and non-carbonic acid weathering, etc. Provided that loss terms are modeled appropriately, the modeling output may be used to account for NFZ loss terms (in the term C_{loss} of the CORC equation, eq. 5.1) for the areas covered by model extrapolation of empirical measurements.

e. **Extrapolation:** Models validated with site-specific empirical data may be used for spatial and temporal extrapolation with the following constraints:

    i. Spatial extrapolation: models may be used to extrapolate across a single homogeneous stratum based on measurements taken in the evaluation area of that stratum. This implies that sampling in the non-evaluation portion of the application site may be replaced by extrapolation of evaluation-area measurements with an appropriate model.

    ii. Temporal extrapolation (seasonal): models may be used to extrapolate across seasonal time frames to the extent that they have been calibrated and validated with empirical data reflecting those seasonal differences.

    iii. Temporal extrapolation (inter-annual): models may be used to extrapolate from one year to the next but not across multiple years, i.e., model validation underlying the simulation of a given year shall be done on site-specific data that were taken no earlier than the previous year.

f. **Uncertainty**: the model shall quantify the uncertainty associated with its outputs (see section 10.5).

    i. The uncertainty assessment shall include estimation of errors arising from the simulation itself as well as the treatment of modeled phenomena (see rule 10.5.6 b).

    ii. If models are used to contribute to the quantification of CORCs, the associated modelling uncertainty shall be included in the evaluation of the total uncertainty of the net CO_2 removal activity (i.e. $u_c(CORC)$, see rule 10.5.3).

g. **Statement and justification of model choice and assumptions:**

    i. The CO_2 Removal Supplier shall provide justification for the selection of the process-based models used, including its spatial and temporal resolution, key physical parameters, and all assumptions applied in simulating relevant dynamics. This justification shall be subject to review and approval by an independent third party as part of the Production Facility Audit.

    ii. The CO_2 Removal Supplier shall describe and justify all assumptions made within the simulation, defining the conditions under which each assumption is considered valid.

    iii. All assumptions and references shall be included in the Monitoring Plan.

    iv. All external references, including data sources, models, and supporting literature, shall be cited and their relevance to the simulation and project context thoroughly explained.

    v. All external references used in the simulation shall be clearly indicated and explained.

h. **Model optimization**: optimization of the model can improve accuracy and reduce uncertainty. Therefore, the following model optimization strategies shall be applied:

    i. Sensitivity analyses of model performance covering ranges of uncertainty of important parameters (e.g. initial feedstock reactive surface area, kinetic coefficients, precipitation, etc.).

    ii. Checks on internal robustness (e.g. butterfly effects, numerical instabilities).

i. **Model output validation**: In order to validate the model output, the following requirements shall be met:

    i. The CO_2 Removal Supplier shall provide a standard validation plan that includes an explicit timeframe for the detectability of the empirical validation technique and a plan for mitigating uncertainty due to spatial and temporal variability;

    ii. The simulation approach shall be transparent, and at least the core components should be publicly available;

    iii. The model shall be validated by site-specific empirical data or data that captures these specifics from a regionalised perspective, e.g., via root mean square error evaluation or other goodness-of-fit indicators. Data used for training or calibrating the model must not be used also for validation;

    iv. The model shall be able to predict directly experimentally verifiable weathering signals such as pH, dissolved inorganic carbon, or major cation concentrations;

    v. The model shall be validated against data measured in-field within the relevant homogeneous stratum;

    vi. The model shall pass sanity checks (e.g., the simulated C_{stored} shall not exceed the theoretical maximum capacity for CO_2 removal given applied feedstock amounts, see rule 9.5.3).

j. **Model publication and availability**: The model code should be open-source. Any computer code and datasets behind the simulation should, to the extent possible, be publicly available in data repositories.

k. **Timeline:** The model shall be completed by the time of the Production Facility Audit. Complete site-specific model validation data shall be provided by the time of the Output Audit. Prior to the Output Audit (if not combined with Facility Audit) and for the purpose of demonstrating eligibility and effectiveness of the model, preliminary model validation results may be used, such as an extrapolation based on experimentally determined weathering rates from measurements conducted in a relevant setting (e.g., from a previous pilot project).

13. Reporting Requirements

13.1.1. 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 Enhanced Rock Weathering activity with the requirements of this methodology, as well as the Puro Standard General Rules[100] and other Standard Requirements.[101]

13.1.2. The Output Report shall include supporting documented evidence for each monitoring period described in the Monitoring Plan, in accordance with ISO 14064-2:2019, clause 6.13 “Reporting the GHG project”.[102]

13.1.3. The Output Report shall include, as a minimum:

a. The name of the CO_2 Removal Supplier and operational partners.

b. A brief description of the Production Facility, including size, location, crediting period, type of carbon removal activity, and Puro-approved Methodology version being followed.

c. The date of the report and the time covered by it (monitoring period).

d. A CORC Summary with supporting detailed GHG calculations and evidence. The GHG emission reductions and removals are stated in tonnes of CO_2e. The detailed information may be redacted to protect sensitive commercial information and comply with data providers' end-user license agreements.

e. If applicable, a description of the GHG baseline and demonstration that the GHG emission removals are not over-estimated.

f. The combined percentage uncertainty of measurement of the CORCs issued in the CORC Summary statement.

g. As applicable, an assessment of permanence including any reversal event.

h. If required by the CO_2 Removal Supplier, changes to the Production Facility and Monitoring Plan shall be clearly stated, and evidence of conformity with Puro General Rules[103], the requirements set in this methodology, and other Puro Standard[104] requirements shall be provided for validation by the third-party Validation and Verification Body.

---

[100] Available in the Puro Standard document library.

[101] Ibid.

[102] 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.

[103] Available in the Puro Standard document library.

[104] Ibid.

13.1.4. Delays or changes in the reporting frequency shall be in conformity with Puro Standard General Rules.[105]

13.1.5. 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 Enhanced Rock Weathering activity (see rule 5.2.8). In addition:

a. These records shall include information on the parameter or process monitored (i.e. what was monitored and how), as well as results of any measurements performed.[106]

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.

13.1.6. Data derived from the ERW activity should be made available to the public, e.g., by data submission to public repositories such as the ERW Data Quarry by *Cascade Climate*.

13.1.7. The terminology used in this methodology in relation to monitoring frequency shall be interpreted as detailed in subrules a-b:

a. The following definitions apply to the description of monitoring frequency:

- Monthly monitoring is defined as at least once per calendar month.
- Quarterly monitoring is defined as at least four times per calendar year (once every three months).
- Semi-annual monitoring is defined as at least twice per calendar year (once every six months).
- Annual monitoring is defined as at least once per calendar year.
- Periodical monitoring is defined as monitoring at predetermined, regular temporal intervals decided by the CO_2 Removal Supplier based on site-specific needs as well as any applicable regulations. The monitoring frequency and rationale thereof shall be explained in the monitoring plan.

b. Monitoring activities with a predefined cadence (e.g. quarterly monitoring) shall be evenly distributed throughout the monitoring period (e.g. once every three months for quarterly monitoring). The CO_2 Removal Supplier may make reasonable adjustments to the monitoring schedule for reasons of necessity or practicality, but such adjustments shall not result in any undue or disproportionate delays to the monitoring activities.

---

[105] Available in the Puro Standard document library.

[106] Note also rule 5.2.8 on keeping records of events that affect the quantification of CORCs. Note that these records are at least partly separate, as not all monitoring activities or results thereof necessarily affect the number of CORCs.

References

Abdalqadir, M., Hughes, D., Rezaei Gomari, S., & Rafiq, U. (2024). A state of the art of review on factors affecting the enhanced weathering in agricultural soil: Strategies for carbon sequestration and climate mitigation. *Environmental Science and Pollution Research*, *31*(13), 19047–19070. https://doi.org/10.1007/s11356-024-32498-5

Amann, T., Hartmann, J., Hellmann, R., Pedrosa, E. T., & Malik, A. (2022). Enhanced weathering potentials—The role of in situ CO2 and grain size distribution. *Frontiers in Climate*, *4*. https://doi.org/10.3389/fclim.2022.929268

Amann, T., Hartmann, J., Struyf, E., de Oliveira Garcia, W., Fischer, E. K., Janssens, I., Meire, P., & Schoelynck, J. (2020). Enhanced Weathering and related element fluxes – a cropland mesocosm approach. *Biogeosciences*, *17*(1), 103–119. https://doi.org/10.5194/bg-17-103-2020

Andrews, M. G., & Taylor, L. L. (2019). Combating Climate Change Through Enhanced Weathering of Agricultural Soils. *Elements*, *15*(4), 253–258. https://doi.org/10.2138/gselements.15.4.253

Baek, S. H., Kanzaki, Y., Lora, J. M., Planavsky, N., Reinhard, C. T., & Zhang, S. (2023). Impact of Climate on the Global Capacity for Enhanced Rock Weathering on Croplands. *Earth's Future*, *11*(8), e2023EF003698. https://doi.org/10.1029/2023EF003698

Barbee, G. C., & Brown, K. W. (1986). COMPARISON BETWEEN SUCTION AND FREE-DRAINAGE SOIL SOLUTION SAMPLERS1: *Soil Science*, *141*(2), 149–154. https://doi.org/10.1097/00010694-198602000-00008

Battles, J. J., Fahey, T. J., Driscoll, C. T. Jr., Blum, J. D., & Johnson, C. E. (2014). Restoring Soil Calcium Reverses Forest Decline. *Environmental Science & Technology Letters*, *1*(1), 15–19. https://doi.org/10.1021/ez400033d

Baum, M., Liu, H., Schacht, L., Schneider, J., & Yap, M. (2024). *Mass-Balance MRV for Carbon Dioxide Removal by Enhanced Rock Weathering: Methods, Simulation, and Inference* (Version 1). arXiv. https://doi.org/10.48550/ARXIV.2407.01949

Beck, H. E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A., & Wood, E. F. (2018). Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Scientific Data*, *5*(1), 180214. https://doi.org/10.1038/sdata.2018.214

Beerling, D. J., Kantzas, E. P., Lomas, M. R., Taylor, L. L., Zhang, S., Kanzaki, Y., Eufrasio, R. M., Renforth, P., Mecure, J.-F., Pollitt, H., Holden, P. B., Edwards, N. R., Koh, L., Epihov, D. Z., Wolf, A., Hansen, J. E., Banwart, S. A., Pidgeon, N. F., Reinhard, C. T., … Val Martin, M. (2025). Transforming US agriculture for carbon removal with enhanced weathering. *Nature*, *638*(8050), 425–434. https://doi.org/10.1038/s41586-024-08429-2

Beerling, D. J., Kantzas, E. P., Lomas, M. R., Wade, P., Eufrasio, R. M., Renforth, P., Sarkar, B., Andrews, M. G., James, R. H., Pearce, C. R., Mercure, J.-F., Pollitt, H., Holden, P. B., Edwards, N. R., Khanna, M., Koh, L., Quegan, S., Pidgeon, N. F., Janssens, I. A., … Banwart, S. A. (2020). Potential for large-scale CO2 removal via enhanced rock weathering with croplands. *Nature*, *583*(7815), 242–248. https://doi.org/10.1038/s41586-020-2448-9

Bertagni, M. B., Calabrese, S., Cipolla, G., Noto, L. V., & Porporato, A. M. (2024). *Advancing Enhanced Weathering Modeling in Soils: Systematic Comparison and Validation with Experimental Data*. https://doi.org/10.22541/essoar.170559500.09183720/v1

Bertagni, M. B., & Porporato, A. (2022). The Carbon-Capture Efficiency of Natural Water Alkalinization: Implications For Enhanced weathering. *Science of The Total Environment*, *838*, 156524. https://doi.org/10.1016/j.scitotenv.2022.156524

Bijma, J., Hagens, M., Hammes, J., Planavsky, N., Pogge von Strandmann, P. A. E., Reershemius, T., Reinhard, C. T., Renforth, P., Suhrhoff, T. J., Vicca, S., Vienne, A., & Wolf-Gladrow, D. A. (2025). Reviews and syntheses: Carbon vs. Cation based MRV of Enhanced Rock Weathering and the issue of soil organic carbon. *EGUsphere*, *2025*, 1–29. https://doi.org/10.5194/egusphere-2025-2740

Brus, D. J., Kempen, B., Rossiter, D., Balwinder-Singh, & McDonald, A. J. (2022). Bayesian approach for sample size determination, illustrated with Soil Health Card data of Andhra Pradesh (India). *Geoderma*, *405*, 115396. https://doi.org/10.1016/j.geoderma.2021.115396

Buckingham, F. L., Henderson, G. M., Holdship, P., & Renforth, P. (2022). Soil core study indicates limited CO2 removal by enhanced weathering in dry croplands in the UK. *Applied Geochemistry*, *147*, 105482. https://doi.org/10.1016/j.apgeochem.2022.105482

Buckingham, S., Tipping, E., & Hamilton-Taylor, J. (2008). Dissolved organic carbon in soil solutions: A comparison of collection methods. *Soil Use and Management*, *24*(1), 29–36. https://doi.org/10.1111/j.1475-2743.2007.00130.x

Buendia, C., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S, Osako, A., Pyrozhenko, Y., Shermanau, P., & Federici, S. (Eds.). (2019). *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. IPCC.

Buss, W., Hasemer, H., Ferguson, S., & Borevitz, J. (2024). Stabilisation of soil organic matter with rock dust partially counteracted by plants. *Global Change Biology*, *30*(1), e17052. https://doi.org/10.1111/gcb.17052

C. Ditzler, K. S. (Ed.). (2023). *Soil Survey Manual.* Government Printing Office. https://bibliotecadigital.ciren.cl/handle/20.500.13082/148329

Chen, Y., & Kanan, M. W. (2025). Thermal Ca2+/Mg2+ exchange reactions to synthesize CO2 removal materials. *Nature*, *638*(8052), 972–979. https://doi.org/10.1038/s41586-024-08499-2

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J., Heimann, M., Jones, C., Le Quéré, C., Myneni, R. B., Piao, S., & Thornton, P. (2013). *Carbon and Other Biogeochemical Cycles* (Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 465–570). Cambridge University Press. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter06_FINAL.pdf

Cipolla, G., Calabrese, S., Noto, L. V., & Porporato, A. (2021a). The role of hydrology on enhanced weathering for carbon sequestration I. Modeling rock-dissolution reactions coupled to plant, soil moisture, and carbon dynamics. *Advances in Water Resources*, *154*, 103934. https://doi.org/10.1016/j.advwatres.2021.103934

Cipolla, G., Calabrese, S., Noto, L. V., & Porporato, A. (2021b). The role of hydrology on enhanced weathering for carbon sequestration II. From hydroclimatic scenarios to carbon-sequestration efficiencies. *Advances in Water Resources*, *154*, 103949. https://doi.org/10.1016/j.advwatres.2021.103949

Clark, J. S. (2005). Why environmental scientists are becoming Bayesians. *Ecology Letters*, *8*(1), 2–14. https://doi.org/10.1111/j.1461-0248.2004.00702.x

Clarkson, M. O., Larkin, C. S., Swoboda, P., Reershemius, T., Suhrhoff, T. J., Maesano, C. N., & Campbell, J. S. (2024). A review of measurement for quantification of carbon dioxide removal by enhanced weathering in soil. *Frontiers in Climate*, *6*, 1345224. https://doi.org/10.3389/fclim.2024.1345224

Davison, A. C., & Hinkley, D. V. (1997). *Bootstrap Methods and their Application*. Cambridge University Press. https://doi.org/10.1017/CBO9780511802843

Deng, H., Sonnenthal, E., Arora, B., Breunig, H., Brodie, E., Kleber, M., Spycher, N., & Nico, P. (2023). The environmental controls on efficiency of enhanced rock weathering in soils. *Scientific Reports*, *13*(1), 9765. https://doi.org/10.1038/s41598-023-36113-4

Dietzel, M., Usdowski, E., & Hoefs, J. (1992). Chemical and 13C/12C- and 18O/16O-isotope evolution of alkaline drainage waters and the precipitation of calcite. *Applied Geochemistry*, *7*(2), 177–184. https://doi.org/10.1016/0883-2927(92)90035-2

Dietzen, C., Harrison, R., & Michelsen-Correa, S. (2018). Effectiveness of enhanced mineral weathering as a carbon sequestration tool and alternative to agricultural lime: An incubation experiment. *International Journal of Greenhouse Gas Control*, *74*, 251–258. https://doi.org/10.1016/j.ijggc.2018.05.007

Dietzen, C., & Rosing, M. T. (2023). Quantification of CO2 uptake by enhanced weathering of silicate minerals applied to acidic soils. *International Journal of Greenhouse Gas Control*, *125*, 103872. https://doi.org/10.1016/j.ijggc.2023.103872

Efron, B., & Tibshirani, R. J. (1994). *An Introduction to the Bootstrap*. Chapman and Hall/CRC. https://doi.org/10.1201/9780429246593

Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T., & Tanabe, K. (Eds.). (2006). *2006 IPCC guidelines for national greenhouse gas inventories, Prepared by the National Greenhouse Gas Inventories Programme*. Institute for Global Environmental Strategies.

Ellison, S L R, & Williams, A. (Eds.). (2012). *Quantifying Uncertainty in Analytical Measurement* (3rd ed.) [141pp.]. Eurachem/CITAC. https://repository.oceanbestpractices.org/handle/11329/1449

Epihov, D. Z., Batterman, S. A., Hedin, L. O., Leake, J. R., Smith, L. M., & Beerling, D. J. (2017). N2-fixing tropical legume evolution: A contributor to enhanced weathering through the Cenozoic? *Proceedings of the Royal Society B: Biological Sciences*, *284*(1860), 20170370. https://doi.org/10.1098/rspb.2017.0370

Essington, M. E. (2004). *Soil and Water Chemistry: An Integrative Approach* (1st ed.). CRC Press.

Fischer, C., Arvidson, R. S., & Lüttge, A. (2012). How predictable are dissolution rates of crystalline material? *Geochimica et Cosmochimica Acta*, *98*, 177–185. https://doi.org/10.1016/j.gca.2012.09.011

Gastmans, D., Hutcheon, I., Menegário, A. A., & Chang, H. K. (2016). Geochemical evolution of groundwater in a basaltic aquifer based on chemical and stable isotopic data: Case study from the Northeastern portion of Serra Geral Aquifer, São Paulo state (Brazil). *Journal of Hydrology*, *535*, 598–611. https://doi.org/10.1016/j.jhydrol.2016.02.016

Gelman, A., Vehtari, A., Simpson, D., Margossian, C. C., Carpenter, B., Yao, Y., Kennedy, L., Gabry, J., Bürkner, P.-C., & Modrák, M. (2020). *Bayesian Workflow* (Version 1). arXiv. https://doi.org/10.48550/ARXIV.2011.01808

Giesler, R., Lundström, U. S., & Grip, H. (1996). Comparison of soil solution chemistry assessment using zero-tension lysimeters or centrifugation. *European Journal of Soil Science*, *47*(3), 395–405. https://doi.org/10.1111/j.1365-2389.1996.tb01413.x

Goll, D. S., Ciais, P., Amann, T., Buermann, W., Chang, J., Eker, S., Hartmann, J., Janssens, I., Li, W., Obersteiner, M., Penuelas, J., Tanaka, K., & Vicca, S. (2021). Potential CO2 removal from enhanced weathering by ecosystem responses to powdered rock. *Nature Geoscience*, *14*(8), 545–549. https://doi.org/10.1038/s41561-021-00798-x

Hamilton, S. K., Kurzman, A. L., Arango, C., Jin, L., & Robertson, G. P. (2007). Evidence for carbon sequestration by agricultural liming. *Global Biogeochemical Cycles*, *21*(2), 2006GB002738. https://doi.org/10.1029/2006GB002738

Haque, F., Chiang, Y., & Santos, R. (2019). Alkaline Mineral Soil Amendment: A Climate Change 'Stabilization Wedge'? *Energies*, *12*(12), 2299. https://doi.org/10.3390/en12122299

Haque, F., Khalidy, R., Chiang, Y. W., & Santos, R. M. (2023). Constraining the Capacity of Global Croplands to CO_2 Drawdown via Mineral Weathering. *ACS Earth and Space Chemistry*, *7*(7), 1294–1305. https://doi.org/10.1021/acsearthspacechem.2c00374

Haque, F., Santos, R. M., & Chiang, Y. W. (2020). CO2 sequestration by wollastonite-amended agricultural soils – An Ontario field study. *International Journal of Greenhouse Gas Control*, *97*, 103017. https://doi.org/10.1016/j.ijggc.2020.103017

Haque, F., Santos, R. M., Dutta, A., Thimmanagari, M., & Chiang, Y. W. (2019). Co-Benefits of Wollastonite Weathering in Agriculture: CO_2 Sequestration and Promoted Plant Growth. *ACS Omega*, *4*(1), 1425–1433. https://doi.org/10.1021/acsomega.8b02477

Harrington, K. J., Hilton, R. G., & Henderson, G. M. (2023). Implications of the Riverine Response to Enhanced Weathering for CO2 removal in the UK. *Applied Geochemistry*, *152*, 105643. https://doi.org/10.1016/j.apgeochem.2023.105643

Hartmann, J., Jansen, N., Dürr, H. H., Kempe, S., & Köhler, P. (2009). Global CO2-consumption by chemical weathering: What is the contribution of highly active weathering regions? *Global and Planetary Change*, *69*(4), 185–194. https://doi.org/10.1016/j.gloplacha.2009.07.007

Hartmann, J., West, A. J., Renforth, P., Köhler, P., De La Rocha, C. L., Wolf-Gladrow, D. A., Dürr, H. H., & Scheffran, J. (2013). Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Reviews of Geophysics*, *51*(2), 113–149. https://doi.org/10.1002/rog.20004

Healey, P., Kruger, T., & Lezaun, J. (2024). Responsible innovation in CDR: Designing sustainable national Greenhouse Gas Removal policies in a fragmented and polycentric governance system. *Frontiers in Climate*, *5*, 1293650. https://doi.org/10.3389/fclim.2023.1293650

IUSS Working Group WRB. (2022). *World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps.* (No. 4th edition). International Union of Soil Sciences (IUSS).

Jariwala, H., Haque, F., Vanderburgt, S., Santos, R. M., & Chiang, Y. W. (2022). Mineral–Soil–Plant–Nutrient Synergisms of Enhanced Weathering for Agriculture: Short-Term Investigations Using Fast-Weathering Wollastonite Skarn. *Frontiers in Plant Science*, *13*. https://doi.org/10.3389/fpls.2022.929457

Kantzas, E. P., Val Martin, M., Lomas, M. R., Eufrasio, R. M., Renforth, P., Lewis, A. L., Taylor, L. L., Mecure, J.-F., Pollitt, H., Vercoulen, P. V., Vakilifard, N., Holden, P. B., Edwards, N. R., Koh, L., Pidgeon, N. F., Banwart, S. A., & Beerling, D. J. (2022). Substantial carbon drawdown potential from enhanced rock weathering in the United Kingdom. *Nature Geoscience*, *15*(5), 382–389. https://doi.org/10.1038/s41561-022-00925-2

Kanzaki, Y., Chiaravalloti, I., Zhang, S., Planavsky, N. J., & Reinhard, C. T. (2024). In silico calculation of soil pH by SCEPTER v1.0. *Geoscientific Model Development*, *17*(10), 4515–4532. https://doi.org/10.5194/gmd-17-4515-2024

Kanzaki, Y., Planavsky, N. J., & Reinhard, C. T. (2023). New estimates of the storage permanence and ocean co-benefits of enhanced rock weathering. *PNAS Nexus*, *2*(4), pgad059. https://doi.org/10.1093/pnasnexus/pgad059

Kanzaki, Y., Planavsky, N. J., Zhang, S., Jordan, J., Suhrhoff, T. J., & Reinhard, C. T. (2025). Soil cation storage is a key control on the carbon removal dynamics of enhanced weathering. *Environmental Research Letters*, *20*(7), 074055. https://doi.org/10.1088/1748-9326/ade0d5

Kanzaki, Y., Zhang, S., Planavsky, N. J., & Reinhard, C. T. (2022). Soil Cycles of Elements simulator for Predicting TERrestrial regulation of greenhouse gases: SCEPTER v0.9. *Geoscientific Model Development*, *15*(12), 4959–4990. https://doi.org/10.5194/gmd-15-4959-2022

Kelland, M. E., Wade, P. W., Lewis, A. L., Taylor, L. L., Sarkar, B., Andrews, M. G., Lomas, M. R., Cotton, T. E. A., Kemp, S. J., James, R. H., Pearce, C. R., Hartley, S. E., Hodson, M. E., Leake, J. R., Banwart, S. A., & Beerling, D. J. (2020). Increased yield and CO_2 sequestration potential with the C_4 cereal *Sorghum bicolor* cultivated in basaltic rock dust-amended agricultural soil. *Global Change Biology*, *26*(6), 3658–3676. https://doi.org/10.1111/gcb.15089

Kerr, D. E., Turner, C., Grey, A., Keogh, J., Brown, P. J., & Kelleher, B. P. (2023). OrgAlkCalc: Estimation of organic alkalinity quantities and acid-base properties with proof of concept in Dublin Bay. *Marine Chemistry*, *251*, 104234. https://doi.org/10.1016/j.marchem.2023.104234

Khalidy, R., Haque, F., Chiang, Y. W., & Santos, R. M. (2021). Monitoring Pedogenic Inorganic Carbon Accumulation Due to Weathering of Amended Silicate Minerals in Agricultural Soils. *Journal of Visualized Experiments*, *172*, 61996. https://doi.org/10.3791/61996

Khudhur, F. W. K., MacDonald, J. M., Macente, A., & Daly, L. (2022). The utilization of alkaline wastes in passive carbon capture and sequestration: Promises, challenges and environmental aspects. *Science of The Total Environment*, *823*, 153553. https://doi.org/10.1016/j.scitotenv.2022.153553

Krishnamurthy, R. V., Schmitt, D., Atekwana, E. A., & Baskaran, M. (2003). Isotopic investigations of carbonate growth on concrete structures. *Applied Geochemistry*, *18*(3), 435–444.

Kruschke, J. K. (2015). *Doing Bayesian data analysis: A tutorial with R, JAGS, and Stan* (Edition 2). Academic Press.

Ku, H. (1966). Notes on the Use of Propagation of Error Formulas. *Journal of Research of National Bureau of Standards - C. Engineering and Instrumentation*, *70C*(4), 263–273. https://nvlpubs.nist.gov/nistpubs/jres/70C/jresv70Cn4p263_A1b.pdf

Lackner, K. S., Wendt, C. H., Butt, D. P., Joyce, E. L., & Sharp, D. H. (1995). Carbon dioxide disposal in carbonate minerals. *Energy*, *20*(11), 1153–1170. https://doi.org/10.1016/0360-5442(95)00071-N

Lafarge, T., & Possolo, A. (2015). The NIST Uncertainty Machine. *NCSLI Measure*, *10*(3), 20–27. https://doi.org/10.1080/19315775.2015.11721732

Lei, K., Bucka, F. B., Teixeira, P. P. C., Buegger, F., Just, C., & Kögel-Knabner, I. (2025). Balancing Organic and Inorganic Carbon Dynamics in Enhanced Rock Weathering: Implications for Carbon Sequestration. *Global Change Biology*, *31*(4), e70186. https://doi.org/10.1111/gcb.70186

Leogrande, R., Vitti, C., Castellini, M., Mastrangelo, M., Pedrero, F., Vivaldi, G. A., & Stellacci, A. M. (2021). Comparison of two methods for total inorganic carbon estimation in three soil types in mediterranean area. *Land*, *10*(4), 409.

Lewis, A. L., Sarkar, B., Wade, P., Kemp, S. J., Hodson, M. E., Taylor, L. L., Yeong, K. L., Davies, K., Nelson, P. N., Bird, M. I., Kantola, I. B., Masters, M. D., DeLucia, E., Leake, J. R., Banwart, S. A., & Beerling, D. J. (2021). Effects of mineralogy, chemistry and physical properties of basalts on carbon capture potential and plant-nutrient element release via enhanced weathering. *Applied Geochemistry*, *132*, 105023. https://doi.org/10.1016/j.apgeochem.2021.105023

Lewis, E., & Wallace, D. (1998). *Program developed for CO_2 system calculations* [Dataset]. https://doi.org/10.15485/1464255

Lord, N. S., Ridgwell, A., Thorne, M. C., & Lunt, D. J. (2016). An impulse response function for the "long tail" of excess atmospheric CO_2 in an Earth system model. *Global Biogeochemical Cycles*, *30*(1), 2–17. https://doi.org/10.1002/2014GB005074

Maitre, R. W. L., Streckeisen, A., Zanettin, B., Le Bas, M.J, Bonin, B., Bateman, P., Bellieni, G., Dudek, A., Efremova, S., Keller, J., Lameyre, J., Sabine, P.A., Schmid, R., Sørensen, H., Woolley, A.R., & International Union of Geological Sciences (Eds.). (2005). *Igneous rocks: A classification and glossary of terms: recommendation of the International Union of Geological Sciences, Subcommission on the Systematics of Igneous Rocks* (2. ed). Cambridge Univ. Press.

Manning, D. A. C., Renforth, P., Lopez-Capel, E., Robertson, S., & Ghazireh, N. (2013). Carbonate precipitation in artificial soils produced from basaltic quarry fines and composts: An opportunity for passive carbon sequestration. *International Journal of Greenhouse Gas Control*, *17*, 309–317. https://doi.org/10.1016/j.ijggc.2013.05.012

McDermott, F., Bryson, M., Magee, R., & Van Acken, D. (2024). Enhanced weathering for CO2 removal using carbonate-rich crushed returned concrete; a pilot study from SE Ireland. *Applied Geochemistry*, *169*, 106056. https://doi.org/10.1016/j.apgeochem.2024.106056

McElreath, R. (2020). *Statistical Rethinking: A Bayesian Course with Examples in R and Stan* (2nd ed.). Chapman and Hall/CRC. https://doi.org/10.1201/9780429029608

Mehlich, A. (1984). Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. *Communications in Soil Science and Plant Analysis*, *15*(12), 1409–1416. https://doi.org/10.1080/00103628409367568

Milliken, E., Woodley, A., & Planavsky, N. (2025). *Direct measurement of carbon dioxide removal due to enhanced weathering*. CDRXIV. https://doi.org/10.70212/cdrxiv.2025352.v1

Mills, J. V., Sanchez, Olagaray, N. Y., Wang, H., & Tune, A. K. (2024). *Foundations for Carbon Dioxide Removal Quantification in ERW Deployments*. Cascade Climate.

Papadopoulos, C. E., & Yeung, H. (2001). Uncertainty estimation and Monte Carlo simulation method. *Flow Measurement and Instrumentation*, *12*(4), 291–298. https://doi.org/10.1016/S0955-5986(01)00015-2

Park, K. F., & Shapira, Z. (2017). Risk and Uncertainty. In M. Augier & D. J. Teece (Eds.), *The Palgrave Encyclopedia of Strategic Management* (pp. 1–7). Palgrave Macmillan UK. https://doi.org/10.1057/978-1-349-94848-2_250-1

Pedrosa, E. T., Kurganskaya, I., Fischer, C., & Luttge, A. (2019). A Statistical Approach for Analysis of Dissolution Rates Including Surface Morphology. *Minerals*, *9*(8), 458. https://doi.org/10.3390/min9080458

Perakis, S. S., & Pett-Ridge, J. C. (2019). Nitrogen-fixing red alder trees tap rock-derived nutrients. *Proceedings of the National Academy of Sciences*, *116*(11), 5009–5014. https://doi.org/10.1073/pnas.1814782116

Power, I. M., Hatten, V. N. J., Guo, M., Schaffer, Z. R., Rausis, K., & Klyn-Hesselink, H. (2025). Are enhanced rock weathering rates overestimated? A few geochemical and mineralogical pitfalls. *Frontiers in Climate*, *6*, 1510747. https://doi.org/10.3389/fclim.2024.1510747

Reershemius, T., Kelland, M. E., Jordan, J. S., Davis, I. R., D'Ascanio, R., Kalderon-Asael, B., Asael, D., Suhrhoff, T. J., Epihov, D. Z., Beerling, D. J., Reinhard, C. T., & Planavsky, N. J. (2023). *Initial validation of a soil-based mass-balance approach for empirical monitoring of enhanced rock weathering rates*. https://doi.org/10.48550/ARXIV.2302.05004

Renforth, P. (2019). The negative emission potential of alkaline materials. *Nature Communications*, *10*(1), 1401. https://doi.org/10.1038/s41467-019-09475-5

Renforth, P., & Henderson, G. (2017). Assessing ocean alkalinity for carbon sequestration. *Reviews of Geophysics*, *55*(3), 636–674. https://doi.org/10.1002/2016RG000533

Santos, R. A., Reis, B. R., Azevedo, A. C., & Sermarini, R. A. (2024). Potential Errors in Cation Exchange Capacity Measurement in Soils Amended with Rock Dust: Two Case Studies. *Communications in Soil Science and Plant Analysis*, *55*(3), 329–342. https://doi.org/10.1080/00103624.2023.2268650

Seifritz, W. (1990). CO2 disposal by means of silicates. *Nature*, *345*(6275), 486–486. https://doi.org/10.1038/345486b0

Shi, W., Su, L., Song, Y., Ma, M., & Du, S. (2015). A Monte Carlo approach to estimate the uncertainty in soil CO2 emissions caused by spatial and sample size variability. *Ecology and Evolution*, *5*(19), 4480–4491. https://doi.org/10.1002/ece3.1729

Sokol, N. W., Sohng, J., Moreland, K., Slessarev, E., Goertzen, H., Schmidt, R., Samaddar, S., Holzer, I., Almaraz, M., Geoghegan, E., Houlton, B., Montañez, I., Pett-Ridge, J., & Scow, K. (2024). Reduced accrual of mineral-associated organic matter after two years of enhanced rock weathering in cropland soils, though no net losses of soil organic carbon. *Biogeochemistry*, *167*(8), 989–1005. https://doi.org/10.1007/s10533-024-01160-0

Song, S., Bellerby, R. G. J., Wang, Z. A., Wurgaft, E., & Li, D. (2023). Organic Alkalinity as an Important Constituent of Total Alkalinity and the Buffering System in River-To-Coast Transition Zones. *Journal of Geophysical Research: Oceans*, *128*(8), e2022JC019270. https://doi.org/10.1029/2022JC019270

Strefler, J., Amann, T., Bauer, N., Kriegler, E., & Hartmann, J. (2018). Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environmental Research Letters*, *13*(3), 034010. https://doi.org/10.1088/1748-9326/aaa9c4

Stumm, W., & Morgan. (1996). *Aquatic chemistry: Chemical equilibria and rates in natural waters* (3rd ed.). John Wiley & Sons, Inc. http://choicereviews.org/review/10.5860/CHOICE.33-6312

Suhrhoff, T. J., Reershemius, T., Jordan, J., Li, S., Zhang, S., Milliken, E., Kalderon-Asael, B., Ebert, Y., Nyateka, R., Reinhard, C., & Planavsky, N. (2025). *Updated framework and signal-to-noise analysis of soil mass balance approaches for quantifying enhanced weathering on managed lands*. CDRXIV. https://doi.org/10.70212/cdrxiv.2025390.v2

Suhrhoff, T. J., Reershemius, T., Wang, J., Jordan, J. S., Reinhard, C. T., & Planavsky, N. J. (2024). A tool for assessing the sensitivity of soil-based approaches for quantifying enhanced weathering: A US case study. *Frontiers in Climate*, *6*, 1346117. https://doi.org/10.3389/fclim.2024.1346117

Swoboda, P., Döring, T. F., & Hamer, M. (2022). Remineralizing soils? The agricultural usage of silicate rock powders: A review. *Science of The Total Environment*, *807*, 150976. https://doi.org/10.1016/j.scitotenv.2021.150976

Thorley, R. M. S., Taylor, L. L., Banwart, S. A., Leake, J. R., & Beerling, D. J. (2015). The role of forest trees and their mycorrhizal fungi in carbonate rock weathering and its significance for global carbon cycling. *Plant, Cell & Environment*, *38*(9), 1947–1961. https://doi.org/10.1111/pce.12444

Van Groenigen, J. W., Van Groenigen, K. J., Koopmans, G. F., Stokkermans, L., Vos, H. M. J., & Lubbers, I. M. (2019). How fertile are earthworm casts? A meta-analysis. *Geoderma*, *338*, 525–535. https://doi.org/10.1016/j.geoderma.2018.11.001

Verbruggen, E., Struyf, E., & Vicca, S. (2021). Can arbuscular mycorrhizal fungi speed up carbon sequestration by enhanced weathering? *PLANTS, PEOPLE, PLANET*, *3*(5), 445–453. https://doi.org/10.1002/ppp3.10179

Vicca, S., Goll, D. S., Hagens, M., Hartmann, J., Janssens, I. A., Neubeck, A., Peñuelas, J., Poblador, S., Rijnders, J., Sardans, J., Struyf, E., Swoboda, P., Van Groenigen, J. W., Vienne, A., & Verbruggen, E. (2022). Is the climate change mitigation effect of enhanced silicate weathering governed by biological processes? *Global Change Biology*, *28*(3), 711–726. https://doi.org/10.1111/gcb.15993

Vienne, A., Poblador, S., Portillo-Estrada, M., Hartmann, J., Ijiehon, S., Wade, P., & Vicca, S. (2022). Enhanced Weathering Using Basalt Rock Powder: Carbon Sequestration, Co-benefits and Risks in a Mesocosm Study With Solanum tuberosum. *Frontiers in Climate*, *4*, 869456. https://doi.org/10.3389/fclim.2022.869456

Washbourne, C.-L., Lopez-Capel, E., Renforth, P., Ascough, P. L., & Manning, D. A. C. (2015). Rapid Removal of Atmospheric CO2 by Urban Soils. *Environmental Science & Technology*, *49*(9), 5434–5440. https://doi.org/10.1021/es505476d

White, A. F., Bullen, T. D., Vivit, D. V., Schulz, M. S., & Clow, D. W. (1999). The role of disseminated calcite in the chemical weathering of granitoid rocks. *Geochimica et Cosmochimica Acta*, *63*(13–14), 1939–1953. https://doi.org/10.1016/S0016-7037(99)00082-4

Xu, T., Spycher, N., Sonnenthal, E., Zhang, G., Zheng, L., & Pruess, K. (2011). TOUGHREACT Version 2.0: A simulator for subsurface reactive transport under non-isothermal multiphase flow conditions. *Computers & Geosciences*, *37*(6), 763–774. https://doi.org/10.1016/j.cageo.2010.10.007

Zhang, J. (2021). Modern Monte Carlo methods for efficient uncertainty quantification and propagation: A survey. *WIREs Computational Statistics*, *13*(5), e1539. https://doi.org/10.1002/wics.1539

Zhang, Q., & Tutolo, B. M. (2022). Evaluation of the potential of glauconite in the Western Canadian Sedimentary Basin for large-scale carbon dioxide mineralization. *International Journal of Greenhouse Gas Control*, *117*, 103663. https://doi.org/10.1016/j.ijggc.2022.103663

Zhang, S., Reinhard, C. T., Liu, S., Kanzaki, Y., & Planavsky, N. J. (2025). A framework for modeling carbon loss from rivers following terrestrial enhanced weathering. *Environmental Research Letters*, *20*(2), 024014. https://doi.org/10.1088/1748-9326/ada398

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

END OF METHODOLOGY