Enhanced Rock Weathering

Methodology for CO_2 Removal

Puro Standard

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Methodology for CO_2 Removal

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Contents

Glossary

> **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 single contiguous plot 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 geographical location where weathering material is applied as part of the enhanced rock weathering activity. The application sites together comprise the *Production facility*.

Bicarbonate A trivial name for hydrogencarbonate, a polyatomic anion with the chemical formula $HCO_3{}^-$. Bicarbonate can be formed via deprotonation of carbonic acid during weathering.

Carbonate An ionic compound characterized by the presence of the carbonate ion, a polyatomic anion with the chemical formula $CO_3{}^{2-}$. In this document, the word 'carbonate' can refer to both the carbonate ion itself or an ionic compound consisting of carbonate ions (e.g. calcium carbonate, $CaCO_3$). See *Solid carbonate*.

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

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.

Model A set of equations implemented in computer software 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, including the analysis and interpretation of the predictions produced by the software.

Production facility A facility capable of CO_2 removal according to the present methodology. For enhanced rock weathering, the production facility coincides with the set of all *Application sites*. A single production facility can only contain application sites of sufficiently similar characteristics (in terms of e.g. location, climate conditions, and type of weathering material) as further defined in this methodology.

Simulation An enhanced rock weathering *Model* or the prediction produced by the *Model*. See *Model*.

Solid carbonate A solid compound characterized by the presence of the carbonate ion $CO_3{}^{2-}$, such as calcium carbonate, $CaCO_3$ or magnesium carbonate, $MgCO_3$.

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.

Weathering material The material being spread to a *Production facility*, capable of storing carbon dioxide in the form of *Carbonate* or *Bicarbonate* ions or *Solid carbonate* minerals via chemical reactions. The weathering material can consist of rocks, minerals or other suitable materials such as alkaline waste products (e.g. slag or cement kiln dust).

Weathering rock See *Weathering material*

Weathering signal An experimentally measurable quantity (such as alkalinity or total inorganic carbon) indicative of weathering reactions taking place in the soil and utilized in the quantification of the CO_2 sequestered. Reliable sequestration quantification methods often rely on several different weathering signals measured over a period of time.

Acronyms

CDR Carbon Dioxide Removal

ERA Environmental Risk Assessment

ERW Enhanced Rock Weathering

GHG Greenhouse Gas

IPCC Intergovernmental Panel of Climate Change

LCA Life Cycle Assessment

PTE Potentially Toxic Element

RMSE Root Mean Square Error

tCO_2e Tonnes of CO_2 Equivalents

Chemical species

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

Ca^{2+} Calcium cation

$CaAl_2Si_2O_8$ Anorthite mineral (calcium aluminosilicate)

CH_4 Methane

Cl^- Chloride

CO_2 Carbon dioxide

${CO_3}^{2-}$ Carbonate

H_2CO_3 Carbonic 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

Note to the reader

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

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

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

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

Document history

Edition 2022 v. 2 (October 2024)

As a summary, this update is incorporating learnings, and increasing the level of detail for monitoring and reporting. The layout of the document has been updated, and portions of the text reworded and reordered for clarity. Additional details on the following topics have also been added:

- Sampling of the soil and of the weathering material.
- Monitoring of the soil organic carbon stocks.
- Quantification of uncertainty and losses following rock application (e.g. plant cation uptake, or riverine & oceanic losses).
- When in-field measurements are available, initial (pre-Audit) simulation models are not required.

More detail on the changes is provided below.

Added

- Acronyms: Acronym definitions.
- Chemical species: Chemical species definitions.
- Rule 2.1.1: Added already existing requirements as a numbered rule.
- Rule 3.1.1: Added more detail on the types of projects eligible under the methodology (i.e. soil applications only), based on pre-existing description in the introduction. Further included more detail on what types of application sites can be considered in the same production facility, based on pre-existing rule clarifications.
- Rule 4.4.5: Added recommendation to monitor absorption of major cations through plant tissue sampling.
- Rule 4.4.6: Soil organic carbon measurements.
- Section 6.1: Added general description of CORCs and new equation for CORCs including leakage and losses, based on pre-existing text in the methodology and guidance for CO_2 Removal Suppliers.
- Rule 6.3.1: Added CORC equation as a numbered rule.
- Rule 6.5.1: Added equation to calculate project emissions based on pre-existing description in the methodology.
- Rule 6.5.2: Added detail on calculation of project emissions based on pre-existing description in the methodology.
- Rule 6.5.3: Added detail on updating project emissions, based on pre-existing guidance to CO_2 Removal Suppliers.
- Rule 6.6.1: Added detail on calculation of leakage emissions, based on pre-existing description in the methodology.
- Section 6.7: Added section on common loss pathways in ERW and their quantification, based on pre-existing guidance for CO_2 Removal Suppliers.
- Rule 6.7.1: Added requirement to quantify & account for loss pathways, based on pre-existing mention in the methodology and guidance to CO_2 Removal Suppliers.

- Rule 6.7.2: Added detail on calculation of total losses.
- Rule 6.7.3: Added detail on the loss terms that need to be accounted for and how to quantify them, based on pre-existing guidance for CO_2 Removal Suppliers.
- Section 7.2: Added guidelines for sampling.
- Rule 7.4.3: Added detail on what the monitoring plan needs to cover, based on pre-existing guidance for CO_2 Removal Suppliers.
- Rule 7.4.4: Added detail on what the geochemical assay must include, based on pre-existing guidance for CO_2 Removal Suppliers.
- Rule 7.4.5: Added detail on what the soil analysis must include, based on pre-existing guidance for CO_2 Removal Suppliers.
- Section 8.3: Added references to more models.

Changed

- Updated layout of the document.
- Reordered content for consistency and readability.
- Renamed some (sub)sections for clarity.
- *Application site*: changed definition (now separate from Production Facility).
- *Production facility*: changed definition (now collection of application sites).
- Section 1: Partially rewrote text to improve clarity, including minor additions.
- Rule 3.1.2: Changed to accommodate new definition of Production Facility as a collection of application sites.
- Section 4.2: Minor edits and additions to guidance text on PTEs.
- Rule 4.5.8: Changed to accommodate the new definition of production facility.
- Rule 6.2.4: Changed to include description of empirical quantification approach in addition to modeling approach.
- Rule 6.2.5: Changed to accommodate changes to rule 8.2.1.
- Rule 6.4.1: Combined pieces of text from other requirements as a single rule for clarity. Added requirements for use of control sites and experimental measurements based on pre-existing guidance to CO_2 Removal Suppliers.
- Section 7.3: Minor additions and edits to pre-existing guidelines for quantification methods.
- Rule 7.4.2: Changed to require evidence supporting the project specificity of the quantification approach in general (instead of only the modeling approach).
- Section 8.1: Minor additions and edits to guidelines for ERW models.
- Rule 8.2.1: Changed to allow use of other estimations besides modeling during the pre-Audit stage.
- Rule 8.2.2: Changed to require comparison of initial estimations (if used) with modeled results.

- Rule 8.2.9: Moved a paragraph of text, slightly edited, to subrule 6.4.1 (c).

Fixed

- Several typos and formatting inconsistencies.
- Several minor edits and rewrites of rule texts for clarity without change in meaning.

Removed

- Note to the reader: reasons for starting methodology development (unnecessary for v. 2).
- Section abstracts.
- Section "General principles of verifiable CO_2 Removals in Puro Standard" (section 2 in previous version): deleted as too general (already included in Puro Standard general rules and other standard documents).
- Redundant rules (e.g. rules 5.1.8 and 4.6.1 in previous version, which are included in rules 4.5.4 and 5.1.1).
- Unnecessary rules (e.g. rule 5.1.9 in previous version, which contained no requirements, but only a cross reference for information).

Edition 2022 v. 1 (November 2022) — Initial release

1

Introduction

1.1 Overview

Natural Weathering

In nature, certain minerals naturally bind carbon dioxide from the atmosphere in a process known as chemical weathering (see figure 1). In this process, carbon dioxide from the atmosphere first dissolves in water (e.g. rain droplets), and when this carbonated water comes into contact with rocks, it will react with—and eventually dissolve—the minerals contained in them, releasing so-called *base cations* (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) into the soil. As a result of these chemical reactions, the carbon dioxide that was dissolved in the water is transformed into other more stable carbon-containing molecules (bicarbonate and carbonate), preventing the release of CO_2 back into the atmosphere.

The rock weathering process described above is a natural phenomenon, which removes about 1.1 $GtCO_2e$ from the atmosphere each year [1]. In the context of engineered CO_2 removal, accelerating (or *enhancing*) Earth's natural weathering processes has been considered for almost 30 years [2, 3], and shows significant global CO_2 removal potential [4–6].

Figure 1: Chemical weathering in soil [7]

Enhanced Rock Weathering

In simple terms, Enhanced Rock Weathering (ERW) aims to accelerate the chemical weathering process (i.e. the rate at which minerals dissolve) by spreading finely ground rock powder or other suitable weathering materials (e.g. crushed concrete) to the soil, thus increasing the reactive surface area of the minerals and accelerating their dissolution[1] and subsequent CO_2 removal. More precisely, the weathering material (often e.g. rock dust containing suitable silicate minerals) undergoes hydrolysis and dissolution reactions when exposed to acidity (i.e. protons, H^+) and water in the soil. In the presence of carbonic acid (H_2CO_3, originating from the dissolution of CO_2 in water), these reactions lead to carbon sequestration in the form of bicarbonates and carbonates, as well as release of base cations, as exemplified by the following reaction describing the hydrolysis and dissolution of diopside ($CaMgSi_2O_6$):

$$CaMgSi_2O_{6(s)} + 2\,H_2O_{(l)} + 4\,H_2CO_{3(aq)} \longrightarrow Ca^{2+}{}_{(aq)} + Mg^{2+}{}_{(aq)} + 2\,H_4SIO_{4(aq)} + 4\,HCO^{3-}{}_{(aq)} \quad (1)$$

Note that the above reaction is merely an idealized depiction of the complex system of chemical reactions that occur in the soil. Furthermore, subsequent reactions such as the formation of solid carbonate minerals (e.g. $CaCO_3$) can also occur (see section 1.3).

Overall, several factors affect the rate of mineral dissolution in soil and therefore the carbon sequestration potential of ERW (see section 1.4). The primary goal of ERW techniques is therefore to accelerate and optimize the weathering weathering reactions by:

- Selecting the most reactive types of weathering material (e.g. rock containing minerals such as olivine, augite, wollastonite, diopside, albite, anorthite, oligoclase, labradorite, andesine, nepheline, or leucite). The most suitable weathering materials usually contain minerals with high amounts of magnesium and calcium.[2]
- Increasing the reactive surface area of the weathering material by reducing the average particle size through crushing or grinding.
- Applying the weathering material to locations with optimal soil and climate conditions to promote the weathering reactions (e.g. tropical regions with relatively low pH soils and a hot and humid climate).

Note that while ERW can be carried out in terrestrial, coastal and aquatic environments, this methodology only considers the application of weathering material in terrestrial (land-based) environments, more specifically in soil.[3]

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[1] The effect is similar to eating a lollipop vs. cotton candy: both are made of sugar, but the solid clump of the lollipop takes much longer to dissolve in the mouth compared to the fine strands of cotton candy.

[2] The suitability of natural rocks for enhanced weathering comes from a combination of factors, including volume of rock available, mineral composition, and levels of potentially toxic elements they contain. Therefore, assessing and certifying ERW technologies must also reflect this variability. This methodology does not specify or exclude rock types or weathering material *per se* but sets various constraints, e.g. on acceptable levels of toxicity.

[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 methodology Carbonated Materials. Enhanced weathering in coastal areas and ocean alkalinization are currently (Oct 2024) not covered under the Puro Standard.

1.2 Positive and negative aspects of ERW

Although enhanced rock weathering as a technology shows significant global CO_2 removal potential [4–6] with ample availability of suitable weathering materials and potential co-benefits, there are also several risks and challenges associated with ERW as a CO_2 removal and sequestration method. Some of the main positive and negative aspects of ERW have been summarized in table 1.

Overall, ERW as a science and technology is still developing, and is considered to have a "low technology readiness level", with "medium" scientific evidence and "low" scientific agreement, relative to other removal methods [8, 9]. To date, a comprehensive body of in-field validation data is still missing, and models that do exist have often been only partially validated using e.g. soil pot trial experimental data [10, 11]. However, several ERW projects are currently ongoing around the globe, and the amount of validation data is constantly increasing as new results become available.

Table 1: Positive and negative aspects of enhanced Rock weathering.

Positive aspects	Negative aspects
Enhanced weathering is among the most permanent form of carbon removal, with relatively low risk of natural or anthropogenic reversibility.	Both monitoring and modeling of weathering in field conditions is challenging, owing to the dynamic nature and the spatial and temporal variability of parameters related to natural ecosystems and the relatively slow mineral dissolution reaction rates.
Mineral resources (rock types and application surfaces) are abundant and available in many areas around the globe.	Rock grinding to very fine particle sizes can lead to emission of respirable particles potentially affecting human health.
Rock mining, grinding and spreading are very well established technologies.	Although established technologies, rock mining, grinding, transport and spreading are energy intensive and can be associated with substantial greenhouse gas emissions. This limits the locations where ERW remains net-negative and cost-effective, and depends mainly on the location of the rock and the type of energy consumed (renewable or fossil fuel based).

Continued on next page

Table 1: Positive and negative aspects of enhanced Rock weathering. (Continued)

Positive aspects	Negative aspects
ERW can be associated with positive co-benefits in agriculture [12], such as: • The release of macronutrients (N, P, K, Ca, Mg, S) and micronutrients (B, Mn, Fe, Se, Zn, Mo, Cu, Ni). • Enhancement of agronomic productivity and reduction of fertilizer use. • Improvement of hydrological soil properties such as increased water retention. • Amendment of acidified soils by increasing its pH. • Improvement of surrounding water catchment by mitigating acidification in aquatic ecosystems through the increase in alkalinity.	As part of the dissolution reaction, some rock or mineral types release heavy metals (such as nickel and chromium), which can be toxic if released in high quantities. For example, nickel is an essential micronutrient, but in excess can be harmful for humans and animal life. This might limit application rates in order to mitigate severe negative effects on ecosystems and human health.
The residual waste material from industrial processes (such as cement kiln dust or demolished and returned concrete) can potentially be utilized for ERW approaches to carbon removal.	ERW in soils does not happen immediately after application, but rather spans over multiple years and even decades. It requires the presence of water, thus it is influenced by changes in local climatic conditions and climate change.

1.3 Reaction chemistry & sequestration

Enhanced weathering can be represented by two or three main sets of chemical reactions:

1. CO_2 hydration and dissociation.
2. Mineral hydrolysis and dissolution.
3. Carbonate precipitation.

While the two first reactions are fundamental to rock weathering, the carbonate precipitation process only occurs in specific situations. These reactions are presented below.

CO_2 hydration and dissociation in water

$$CO_{2(g)} \rightleftharpoons CO_{2(aq)} \tag{2}$$

$$CO_{2(aq)} + H_2O_{(l)} \rightleftharpoons H_2CO_{3(aq)} \tag{3}$$

$$H_2CO_{3(aq)} \rightleftharpoons H^+{}_{(aq)} + HCO_3{}^-{}_{(aq)} \tag{4}$$

$$HCO_3{}^-{}_{(aq)} \rightleftharpoons H^+{}_{(aq)} + CO_3{}^{2-}{}_{(aq)} \text{ (only significant at high pH)} \tag{5}$$

Alternative writing:

$$CO_{2(aq)} + H_2O_{(l)} \rightleftharpoons H_2CO_{3(aq)} \rightleftharpoons H^+{}_{(aq)} + HCO_3{}^-{}_{(aq)} \rightleftharpoons 2\,H^+{}_{(aq)} + CO_3{}^{2-}{}_{(aq)} \tag{6}$$

Mineral hydrolysis and dissolution

The actual chemical reaction depends on the mineral considered, but follows the generic pattern below:

$$\text{suitable mineral} + \text{aqueous } CO_2 \longrightarrow \text{cations} + \text{bicarbonate} + \text{secondary silicates/clays} \tag{7}$$

For example, the dissolution of 1 mol of anorthite mineral ($CaAl_2Si_2O_8$) in the presence of CO_2 results in the formation of 2 mol of bicarbonate, and secondary silicates:

$$CaAl_2Si_2O_{8(s)} + 2\,CO_{2(aq)} + 3\,H_2O_{(l)} \longrightarrow Ca^{2+}{}_{(aq)} + 2\,HCO_3{}^{-}{}_{(aq)} + Al_2Si_2O_5(OH)_{4(s)} \tag{8}$$

Note that above, 1 mol of alkali earth metal (here Ca^{2+}) released leads to 2 mol of CO_2 stored.

In the above example CO_2 hydration and dissociation, and mineral dissolution reactions are occurring in parallel. In broad terms, this is what is being defined as weathering.

It is important to note that the reaction leading to CO_2 removal (i.e. mineral hydrolysis and dissolution by protons from carbon dioxide) is in competition with mineral hydrolysis and dissolution by protons from other stronger acids that may be present in the soil,[4] but do not contribute to bicarbonate formation and subsequent CO_2 removal. In addition, bicarbonates formed through the reaction above are mobile and are transported in the water catchment eventually reaching the ocean. Along the way, a fraction of the formed bicarbonates might react further and re-release CO_2 back to the atmosphere e.g. via the formation of carbonate minerals, as detailed below.

Carbonate precipitation

An additional reaction that may happen in specific cases (e.g. highly saturated, high pH, and low moisture soils) is the precipitation of calcium carbonate in the soil.

$$Ca^{2+}{}_{(aq)} + 2\,HCO_3{}^{-}{}_{(aq)} \longrightarrow CaCO_{3(s)} + CO_{2(aq)} + H_2O_{(l)} \tag{9}$$

This results in 1 mol of CO_2 *released back to the atmosphere*. Compared to the mineral dissolution reaction presented above (2 mol CO_2 stored per 1 mol of Ca^{2+} released), the carbon capture efficiency is reduced: out of the 2 mol of CO_2 that were stored, 1 mol is re-emitted. However, note that depending on the environment, the above precipitation reaction can also occur in the reverse direction leading to re-dissolution of $CaCO_3$ and sequestration of CO_2.

Ultimate fate of dissolved carbon

In soils, the above reactions (CO_2 hydration and dissolution. mineral dissolution, and carbonate precipitation) happen in parallel and in the same space (so-called *direct weathering*), as opposed to controlled environments, where dissolution and precipitation can be designed to occur in separate reactors (allowing for optimization of each reaction in what is known as *indirect weathering*). Therefore, ERW in soils can lead to the formation of both carbonates and bicarbonates in variable proportions determined by the local environmental conditions.

- The bicarbonates that are dissolved in the soil water can leach from the soil into the groundwater, and can reach river streams and oceans, where CO_2 remains stably sequestered as bicarbonates in water, or precipitate in the ocean as solid carbonate minerals (calcite). In general this counteracts in a positive sense the acidity of these aquatic ecosystems through alkalinity addition.

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[4] For example, nitric acid from overuse of fertilizers or sulphuric acid from pollution.

- When solid carbonate minerals form, they become part of the soil, and CO_2 remains stably sequestered directly in soils, as long as the local soil pH does not become too acidic. In the case where the carbonate minerals do dissolve, they can re-form bicarbonates and re-sequester the CO_2 that was released upon initial precipitation.

1.4 Factors affecting the weathering rate

Whenever a mineral/rock is in contact with water it will tend to react. The type of reaction and its rate is affected by many physical, chemical and even biological parameters, but in general, dissolution is mainly driven by undersaturation. The weathering reactions are limited by the hydrolysis/dissolution of silicates in water. The mineral dissolution reaction freeing cations is slower than the dissolution of CO_2 in water and the carbonate-forming precipitation. In general, the timing of carbon removal via ERW in soils, which are natural systems, often spans over months to decades following weathering material application to soil. This contrasts with weathering in engineered systems, where dissolution and precipitation reactions can be controlled to occur within days to minutes.

Due to the multitude and intricate nature of the chemical reactions taking place in the soils, the overall weathering rate is affected by several factors, as elaborated in more detail below. However, in broad terms, ideal conditions for weathering often include:

- Low pH.
- High water availability.
- High temperature.
- High CO_2 partial pressure.
- Increased reactive surface area.

Type of acid

The presence of strong acids (e.g. nitric or sulfuric acid) in soils can impact the weathering rate, but not lead to carbon sequestration. Strong acids can be present in e.g. intensively farmed agricultural land (nitric acid from overuse of nitrogenous fertilizers), or when soils are impacted by acid rain (sulphur oxide emissions producing sulphuric acid).

Surface area

The velocity at which a mineral grain dissolves in water is proportional to the specific surface area of the material. Although the normalized *reaction rate* (defined e.g. in units of $\mathrm{mol\,m^{-2}\,s^{-1}}$, i.e. amount of substance dissolved per surface area and time) remains the same, in absolute terms the increased surface area leads to faster dissolution. In other words, smaller particles take less time to fully dissolve. Therefore, the process of rock crushing and milling improves the rate of enhanced weathering by increasing the surface area available to react, and also by introducing defects at the mineral's surface [13, 14]. The ideal grain size for ERW is not comprehensively known, although some studies suggest the existence of a lower limit in particle size for effective weathering [15]. In practical terms, the ideal particle size is dependent on several factors unrelated to the dissolution chemistry itself, such as the cost and energy efficiency of grinding, or the potential difficulties and/or hazards related to handling very fine dusts.

Temperature

The rate of mineral dissolution is also linked to temperature through an Arrhenius equation (exponential relationship): even small increases in temperature can lead to significantly higher silicate dissolution rates (although some minerals, such as portlandite and calcite, exhibit higher solubility in lower temperatures). Therefore, warm tropical regions (also known for their highly weathered and acidic soils) can be optimal areas for faster ERW.

Aqueous phase composition

The chemical composition of the water also affects reaction kinetics. In particular, lower pH typically accelerates silicate dissolution (and hinders carbonate precipitation), with different relationships and threshold levels for different minerals. The chemical composition, ionic strength, and saturation conditions of the pore waters in relation to the different mineral species affect chemical reactions in a complex fashion (see e.g. [16, 17]). The weathering material composition itself and its surface passivation also affect the kinetics of dissolution (e.g. [18]).

Biotic factors

Many biotic factors may also affect the weathering rate. Plants may enhance silicate mineral weathering in soils through their roots and associated mycorrhizal fungi, via diverse mechanisms such as the release of organic acids [19–21], the secretion of acids, or stimulation of acid-generating nitrification by nitrogen-fixing plants [22–24]. As our understanding of this domain continues to evolve, grasping the intricate relationship between mycorrhiza and weathering rates will emerge as an important dimension to explore. Invertebrates in soil also contribute to weathering: chemically through the action of gut microbiota, and mechanically by bioturbation [25, 26].

2

Point of creation of the CO_2 Removal Certificate (CORC)

2.1 CO_2 Removal Supplier

2.1.1 The CO_2 Removal Supplier is the authorized party to represent the end-to-end supply chain of the enhanced rock weathering (ERW) activity. The CO_2 Removal Supplier is responsible for making end-to-end data available and accessible for 3rd party verification. This includes delivering data needed to assess the eligibility of the activities, quantify the predicted net carbon removal, and monitor the actual removal rate after application.

2.2 Point of creation

The CO_2 removal certificates associated with a given enhanced weathering project shall be issued gradually over the lifetime of the project, following the application of the weathering material. In practice, it can take several years or even decades for all the CORCs associated with a given project to be issued, depending on the speed of the weathering reactions taking place.[5]

2.2.1 The amount of CORCs issued at a given time shall be based on the actual amount of CO_2 sequestration that has *already happened* so far, as verified by the in-field measurements performed by the CO_2 Removal Supplier.

2.2.2 CORCs can be issued at any point in time after the application of the weathering material provided that the CO_2 Removal Supplier is able to produce evidence in the form of in-field measurements quantifying the amount of CO_2 already sequestered (see sections 6.4 and 7.4).

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[5] Although this methodology does not require or endorse any particular funding solution for commercial projects, it can be noted that the eventual funding gaps associated with long return periods would need to be bridged with the project's own equity, or via various other means of funding.

3

Eligibility requirements and verification

3.1 General eligibility requirements

3.1.1 An eligible activity is an activity capable of storing carbon dioxide in the form of carbonate and bicarbonate ions or solid carbonate minerals via the application of a weathering material to one or several application sites, as further detailed in subrules (a) and (b).

(a) The weathering material shall only be applied to the soil, and 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.

(b) All application sites comprising the Production Facility shall be subject to the same environmental and other relevant regulations, and have broadly consistent:

- Geographic location.
- Climatic conditions.
- Type of applied feedstock (see rule 7.4.4).
- Soil type (see rule 7.4.5).
- Risk profile related to potentially toxic elements (PTE risk).

3.1.2 For the purposes of this methodology, the set of all application sites corresponds to the Production Facility of CO_2 Removal Certificates, as per the terminology defined in the Puro Standard General Rules.[6] The Production Facility can consist of physically separated application sites, and need not be contiguous.

3.1.3 A Production Facility and the associated activity is determined as eligible for issuance of CO_2 Removal Certificates, once the Production Facility has undergone a process of third-party verification by a duly appointed auditor performing a Production Facility Audit.

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

(b) The CO_2 Removal Supplier may expand the Production Facility with additional application sites conforming to rule 3.1.1 without having to undergo a new Production Facility audit, provided that such additions are approved by the Issuing Body and verified during an Output audit.

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[6] Available in the Puro Standard documents library.

3.1.4 The Production Facility Auditor collects and checks the standing data of the CO_2 Removal Supplier and the Production Facility. The standing data to be collected by the Auditor includes:

- A certified trade registry extract or similar official document stating that the CO_2 Removal Supplier's organization legitimately exists.
- The CO_2 Removal Supplier registering the Production Facility in the Puro Registry.
- Locations of the application sites forming the Production Facility.
- Whether the Production Facility has benefited from public financial support.
- Date on which the Production Facility becomes eligible to issue CORCs.

3.2 Requirements for additionality

3.2.1 The CO_2 Removal Supplier shall be able to demonstrate additionality,[7] meaning that the project must convincingly demonstrate that the CO_2 removals are a result of carbon finance. Even with substantial non-carbon finance support, projects can be additional e.g. if investment is required, risk is present, and/or human capital must be developed.

3.2.2 To demonstrate additionality, the CO_2 Removal Supplier must show that the project is not required by existing laws, regulations, or other binding obligations.

3.2.3 To demonstrate additionality, the CO_2 Removal Supplier must provide full project financials and counter-factual analysis based on baselines that shall be project-specific, conservative and periodically updated.

3.3 Requirements for prevention of double-counting

3.3.1 The CO_2 Removal Supplier shall ensure that the CO_2 removals from the ERW activity shall not be double-counted nor double-claimed. The carbon removal credit must solely be registered in Puro.earth's carbon removal registry. The upstream and downstream commercial relationships between the supply-chain partners shall prevent double-counting and double-claiming of the carbon removal.

3.3.2 To demonstrate no double-counting, the CO_2 Removal Supplier must evidence with documents that the weathering material suppliers are prevented from making claims to include the carbon net-negativity, carbon removal, carbon drawdown or carbon sink aspects of the ERW activity.

3.3.3 To demonstrate no double-counting, the CO_2 Removal Supplier must also evidence with documents that the land-owners or land-users receiving the weathering material to their soils are prevented from making claims to include the carbon net-negativity, carbon removal, carbon drawdown or carbon sink aspects of the ERW activity.

3.3.4 The resulting carbon removal shall not be used in marketing of any products arising as a part of the supply-chain (e.g. other mined rocks, agricultural or forestry products). However, supply-chain partners can claim their affiliation to the ERW activity, in coordination with the CO_2 Removal Supplier.

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[7] Removals are additional if they would not have occurred without carbon finance. The CO_2 Removal Supplier must measure the removals claimed against a baseline which should represent a conservative scenario for what would likely have happened without carbon finance (the "counterfactual").

4

Social and Environmental Safeguards

4.1 General principles

From an environmental perspective, one major risk associated with ERW projects is the addition to soil of potentially toxic elements (PTEs) or contaminants. Depending on the weathering material used, PTEs may include heavy metals, radionuclides, or asbestiform minerals.

All projects seeking to certify their carbon removal activity with Puro Standard are required to avoid—whenever possible—negative impacts to society, and the environment.[8] Beyond simply avoiding harm, ideal projects will pursue co-benefits for instance by protecting ecosystems and biodiversity, supporting water conservation, and advancing sustainable livelihoods and environmental justice.[9]

4.2 Guidance on risk evaluation of potentially toxic elements

During the weathering reactions, elements are released into 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 including 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 direct exposure to contaminated soil, ingestion through the food chain or contaminated water). It is worth noting that many potentially toxic elements also have an essential role in biological processes as micronutrients. To date, most of the knowledge available refers to heavy metals in weathering materials, while radionuclides and asbestos are less studied in the context of enhanced weathering.

Risk assessment outline

- **Step 1. Problem Formulation**
  This step defines the problem, scope and goal of the risk assessment. The problem formulation must be specific to the ERW activity considered. The application of weathering material at a specified application site (e.g. agricultural soil, forest soil, urban soil) may introduce heavy metals, radionuclides and asbestiform minerals at levels leading to harmful effects on the local ecosystem (fauna and flora), humans affected directly or indirectly from the application site (recreational use, occupational use, food chain), or by contamination of water reserves. The purpose of the risk assessment is to evaluate the specific risks of a given project, in light of local conditions, and what needs to be protected.

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[8] Current knowledge on the environmental risks associated with PTEs or contaminants present in weathering materials is briefly summarized in section 4.2.

[9] See e.g. the Microsoft criteria for high-quality carbon dioxide removal.

- **Step 2.1. Hazard characterisation**
  This step defines what are the elements of concern (what metals, asbestiform minerals or radionuclides), what are the pre-existing levels at the application sites (i.e. soil sampling and analysis), what are the concentrations added by the weathering project (i.e. rock sampling and analysis), and what are the dynamics and mechanisms associated with the addition of these elements at the application sites. This depends both on the weathering material selected, and the local conditions at the application sites.
- **Step 2.2. Exposure characterisation**
  This step defines what are the exposure pathways through which the elements of concern (metals, asbestiform minerals and/or radionuclides) can reach humans, fauna, flora, and water resources. It also assesses the likelihood and seriousness of these exposure pathways. For ERW on agricultural soils: plant uptake, food chain exposure, occupational hazard for the farmers and workers, and water resource contamination are of particular interest. For ERW on forest soils, biodiversity exposure, human recreational and occupational exposure, and water resource contamination are of particular interest. Wind erosion may also be of general concern.
- **Step 3. Risk characterisation**
  This step combines the finding from the hazard and exposure characterisation steps, to determine the level of risk. This step shall also include an evaluation of the legality of the activity, based on local, national or regional regulations.
- **Step 4. Risk mitigation measures**
  This step may define risk mitigation and prevention measures that can bring the risk to levels of no harm or below acceptable limits. For ERW on agricultural soils, such measures may include for instance:
  - Cultivation of food crops that do not uptake specific metals of concerns.
  - Cultivation of energy crops that actually uptake the metals of concerns, for subsequent incineration and storage of ashes.
  - Other phytoremediation methods.
  - Addition of biochar for metal immobilization.
- **Step 5. Conclusion regarding the ERW activity**
  The conclusion shall summarize the overall risk of the ERW activity. It shall also provide a short statement on applicability and legality of the activity. For instance, the conclusion can state whether an activity is:
  - Permitted, with no major risks.
  - Permitted provided that adequate mitigation measures are implemented.
  - Not permitted due to non-manageable risk.

Heavy metals

The levels and effects of heavy metals in agricultural and forest soils have been studied for decades. In some parts of the world, estimates of heavy metal concentrations in soils are available (e.g. [27]), and several guidelines and laws exist to regulate the addition of heavy metals to soils.

The limits defined in such regulations may take the form of:

- **Maximum metal concentrations in the applied material** (e.g. expressed in mg of metal per kg of fertilizer), e.g. the EU has compulsory regulation for fertilizers.[10]
- **Maximum metal application rates** (e.g. expressed in kg metal per hectare and per year).
- **Maximum metal concentrations present in soils** (e.g. expressed in mg metal per kg soil, or ppm), e.g. the European Joint Research Center has compared thresholds defined in various Member State countries [28].
- **A combination of the above-mentioned limit types**, e.g. in the context of sewage sludge application to soil, the EU sludge directive has defined maximum concentrations in the sludge, maximum concentrations in the soil, and maximum addition over a 10 year period.[11] Each member state then ratified the directive with adjustments of thresholds to specific local conditions, e.g. in the United Kingdom by types of soil use (arable land, grassland) and pH levels.[12]
- **Maximum bioavailable metal concentrations in soils.** The notion of bioavailability of a substance is another way of assessing environmental risks. Assessment methods based on bioavailability are usually perceived as less conservative and are still associated with multiple quantification challenges (e.g. large variability within soil and crop types). Nevertheless, bioavailability may still be relevant to consider in well-defined situations (e.g. determination of chromium speciation in high chromium concentration weathering materials, or in regions where agricultural soils have naturally occuring high concentration of nickel and where an ERW project could reduce nickel bioavailability).

Limit values usually take into account specific parameters related to the activity (e.g. frequency of application) but also factors related to the fate of PTEs in soil, such as vertical soil mobility, plant uptake, export to water resources, and exposure pathways to humans.

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[10] Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilizing products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003.

[11] 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.

[12] Environment Agency, United Kingdom (2018). Guidance on Sewage sludge in agriculture: code of practice for England, Wales and Northern Ireland

Examples of toxicity limits

Maximum metal concentrations in the weathering material

The fertilizer regulation in the EU is based on a maximum metal concentration *in the applied amendment*, with multiple limits depending on amendment type, e.g. organic, mineral, organo-mineral, in liquid or solid forms. In particular, threshold values have been defined for so-called *inorganic soil improvers* (e.g. rock dust, crushed rocks), within a specific agricultural context and a particular level of risk (see table 2). Re-using these threshold values in the context of ERW might indicate a safe ERW activity if the ERW activity has equal or lower application rates than inorganic soil improver amendments. However, some weathering materials are known to have higher concentrations of some PTEs (e.g. nickel) than prescribed in table 2, but may still be deemed safe to use according to soil maximum concentrations or other context-specific factors.

Table 2: Limit values for heavy metal contents in inorganic soil improver, reproduced from Annex I, PFC 3(B), in the EU regulation for fertilizing products[a]

Metal	Limit ($\mathrm{mg\,kg^{-1}}$ dry matter)
Cadmium (Cd)	1.5
Hexavalent chromium (Cr VI)	2.0
Mercury (Hg)	1.0
Nickel (Ni)	100
Lead (Pb)	120
Inorganic arsenic (As)	40
Copper (Cu)	300
Zinc (Zn)	800

[a] Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilizing products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003.

Maximum metal concentrations in the soil (top 30 cm)

Evaluating heavy-metal risks in ERW projects using threshold values from maximum concentrations in soils requires measurement of background (pre-project) concentration levels, measurement of the amount of heavy metals to be applied, as well as the existence of maximum guideline values. These can vary between states, regions or countries, as well as with type of land use or soil properties. Guidelines from several European countries were reviewed in [28], while other international guidelines were compiled in [29, table S2]. An example of such guideline values is presented in table 3, and is taken from the Finnish governmental decree on the Assessment of Soil Contamination and Remediation Needs (2007).[13] Values from this decree are presented here as relevant for agricultural soils following precedents in academic literature [27] and international UN reports [30].

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[13] Ministry of the Environment, Finland (2007). Government Decree on the Assessment of Soil Contamination and Remediation Needs.

Table 3: Limit values for metal contents in soils derived from the Finnish governmental decree on the Assessment of Soil Contamination and Remediation Needs (2007).[a]

Metal	Limit ($\mathrm{mg\,kg^{-1}}$ dry matter)
Cadmium (Cd)	1.0
Chromium (Cr)	100
Mercury (Hg)	0.5
Nickel (Ni)	50
Lead (Pb)	60
Arsenic (As)	5.0
Copper (Cu)	100
Zinc (Zn)	200
Cobalt (Co)	20
Antimony (Sb)	2.0
Vanadium (V)	100

[a] Ministry of the Environment, Finland (2007). Government Decree on the Assessment of Soil Contamination and Remediation Needs.

Asbestos

Asbestos and asbestiform minerals are a type of naturally occurring fibrous silicate material that can cause serious human health risks via exposure through inhalation. The most common type of asbestos belongs to the serpentine group, namely chrysotile (white asbestos). Asbestos can occur in clays such as muscovite, and it is also common in rocks from the amphibole group including amosite, crocidolite, and tremolite. Asbestos chemically reacts with CO_2 to form carbonates and has been pointed out as one of the best materials for mineral carbonation [31]. However, due to the health risks, the carbonation needs to be performed safely under closed laboratory/reactor conditions, and fully avoided in ERW practices.

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. The significance of this potential risk in ERW projects is not sufficiently studied. However, it is likely that rock mining operations are already regulated with respect to asbestos risks, and maximum threshold values exist for other products. For instance, the UK Health and Safety Executive defines, for construction materials, that risks are negligible when asbestos is present within materials at trace levels [32]. Trace level is itself defined as the presence of only "one or two fibers" during the analysis of bulk materials for asbestos by the recognised polarized light microscopy (PLM) method HSG248 [32]. It is further specified that asbestos levels above trace amounts are not necessarily of concern if the material is not subject to particle size reduction. However, 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.

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. However, the significance of this potential risk in ERW projects is not sufficiently studied.

4.3 Requirements for social safeguards

4.3.1 The CO_2 Removal Supplier shall demonstrate and evidence engagement with local communities in an ongoing and transparent manner throughout the project lifetime.

4.3.2 The CO_2 Removal Supplier shall not operate on land that has been identified as culturally sensitive or cause community displacement.

4.3.3 The CO_2 Removal Supplier shall demonstrate and evidence that projects have a low risk of any materially negative impacts on the surrounding local communities. Where applicable, the CO_2 Removal Supplier shall provide documented information on the effects on local communities, indigenous people, land tenure, local employment, food production, user safety, and cultural and religious sites, *inter alia*.

4.3.4 The CO_2 Removal Supplier shall inform, during public stakeholders consultations, the local community of the acceptability limits for contaminants followed in these projects. As part of the stakeholder consultation, the CO_2 Removal Supplier shall communicate the potential health risks and limits concerning toxic contaminants in the applied weathering material.

4.3.5 To demonstrate local stakeholder consultation, the CO_2 Removal Supplier shall be able to provide documented evidence on how they informed and acquired consent from local communities and other affected stakeholders. The documented information shall detail the procedures for continued dialogue with the local community after the weathering material is applied to the soil. The CO_2 Removal Supplier shall be able to demonstrate with documents the policy and procedures in place to address potential grievances.

4.3.6 The CO_2 Removal Supplier shall be able to present measures taken for occupational health and safety hazards during operation or the ERW activity. The activities (e.g. crushing, grinding, spreading) shall be performed in accordance with local regulations (e.g. noise limits, dust emission limits, occupational health and safety).

4.4 Requirements for environmental safeguards

4.4.1 The CO_2 Removal Supplier shall demonstrate and evidence that projects have a low risk of any materially negative impacts on the surrounding ecosystems (including soil health, biodiversity, water, air pollution).

4.4.2 The CO_2 Removal Supplier shall demonstrate safe weathering material sourcing, including the origin of the raw materials, and that the raw material is sourced sustainably in accordance with local regulations (in particular, mining regulations). Any exploitation permit, land use right, environmental permits, as well as certification of operations, shall be part of the proof.

4.4.3 The CO_2 Removal Supplier shall provide evidence regarding the right or authorisation to spread the weathering material onto the application sites.

4.4.4 The CO_2 Removal Supplier shall be able to demonstrate that the weathering material sourcing and application activities do no significant harm to the surrounding natural environment or local communities.

4.4.5 The CO_2 Removal Supplier shall follow the impact on crops after the application of weathering material to agricultural soils, as this application can affect the quality and yield of crops [12, 33]. The further monitoring of the absorption of major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) by plants is recommended (e.g. via analysis of plant tissue samples, see also rule 6.7.1 and subrule 6.7.3 (c)).[14]

4.4.6 The CO_2 Removal Supplier shall follow the impact of the enhanced rock weathering activity on soil organic carbon stocks at the application sites, or a representative subset thereof, through periodic measurements of soil organic carbon content in accordance with the monitoring plan of the CO_2 Removal Supplier.

Note that at present, the requirement to monitor soil organic carbon stocks is for purposes of research and information gathering only, and does not affect the quantification of CORCs.

4.5 Requirements for environmental risk assessment and management

4.5.1 The CO_2 Removal Supplier is the entity responsible for assessing the environmental risks associated with the ERW activity at the specific site of application and in the receiving catchment, via an environmental risk assessment. The CO_2 Removal Supplier is the entity responsible for managing the environmental risks associated with the ERW activity and for implementing the measures defined in the risk assessment.

4.5.2 The CO_2 Removal Supplier is responsible for following any existing regulation in the jurisdiction where the activity takes place, especially with respect to the concentration limits of potentially toxic elements, e.g. in soil, in water, or in the weathering material used. In other words, if country-specific threshold values exist and are more stringent than other recommended values in this methodology, the country-specific values shall prevail.

4.5.3 The CO_2 Removal Supplier shall provide information to all involved stakeholders (e.g. local community, land owner, local municipality, investors, credit buyers) about the environmental risks associated with the ERW activity at the specific site of application and in the receiving catchment.

4.5.4 The CO_2 Removal Supplier shall perform an environmental risk assessment (ERA) for the application of weathering material at the application sites, resulting in acceptable and manageable risks. Compliance with any local regulation, as per the requirements for potentially toxic elements is also required.

4.5.5 The environmental risk assessment performed by the CO_2 Removal Supplier shall follow the guidance from the US EPA,[15] the EU EFSA,[16] or other locally relevant institutions. The environmental risk assessment shall contain the follow the outline below (see details in subsection Risk assessment outline of section 4.2):

- Step 1. Problem Formulation

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[14] Removal of major cations from the soil following weathering can affect the equilibria of the chemical reactions governing the sequestration of CO_2 by weathering, and diminish the amount of CO_2 permanently sequestered.

[15] About Risk Assessment | US EPA

[16] Environmental risk assessment | EFSA

- 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

4.5.6 Where there is no local regulation guiding the acceptability of levels of potentially toxic elements, EU thresholds shall be used as the threshold limits (see section 4.2).

4.5.7 When there is a local regulation setting contaminant thresholds that differ to those set by the EU,[17] the local thresholds should be followed. Where the EU threshold limits are more stringent than local regulation a contextual justification is required within the ERA.

4.5.8 The ERA shall be completed before the decision was taken to apply weathering material at the potential Production Facility.

4.5.9 The environmental risk assessment shall be conservative in its assumptions and calculations.

4.5.10 The environmental risk assessment shall be reviewed by an independent third-party, with relevant expertise.

4.5.11 The CO_2 Removal Supplier shall provide evidence, in the form of laboratory results, that supports the conclusions reached in the ERA. This includes, but is not limited to, results from laboratory analyses of the weathering material (see rule 7.4.4) and the soil samples (see rule 7.4.5), determining concentrations of potentially toxic elements with appropriate methods (see also section 4.2).

4.5.12 The ERA and its supporting evidence will be subject to an internal screening by Puro and to an external validation by an independent third-party.

4.5.13 The environmental risk assessment shall focus on prevention of the environmental risks, for example:

- Proper selection of crushed materials to minimize amounts of PTEs applied: for instance, silicate rocks with low content of heavy metals are preferred over other rocks.
- Proper site selection of land types: acidic arable and forest lands are most appropriate with no harmful effects to water resources. Degraded (e.g. polluted and eroded) land could be considered to combine restoration of the land and CO_2 removal.
- Proper analysis of food safety: the effects of crushed material applications on the quality and yield of crops from published studies.

4.5.14 The CO_2 Removal Supplier shall consider, quantify and discuss heavy metal related risks in the ERA. This shall at least include: i) a metric based on maximum concentration in the soil, and ii) a metric based on maximum concentration in the weathering material. The relevance (or irrelevance) of each metric must be explained and justified, for each specific ERW project.

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[17] Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilizing products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003.

4.5.15 The CO_2 Removal Supplier shall consider and discuss asbestos related risks in the ERA and demonstrate that asbestiform minerals are not present above trace levels.

4.5.16 The CO_2 Removal Supplier shall consider and discuss radionuclide related risks in the ERA.

5

Assessment of life cycle greenhouse gas emissions

5.1 LCA and process boundaries

5.1.1 For the purpose of CORC determination, the CO_2 Removal Supplier shall provide a life cycle assessment (LCA) for the Enhanced Rock Weathering (ERW) activity, following the general guidelines for LCA defined in the ISO standards 14040/44 and following the LCA scope defined in this section. The LCA shall include a report that explains and justifies the data and modeling choices made, as well as all supporting calculation files that will be used for calculation of CORCs.

5.1.2 An ERW activity or project is defined in the LCA as the application of a given type and amount of material (expressed in dry metric tonnes), to a specific soil location (with a well-defined area and geolocation), at a given average application rate (in dry tonnes per hectare), with specific material granulometry, and soil incorporation process and depth. This forms the functional unit of the LCA. In case of multiple applications of material on the same field, over multiple years, each application is seen as a separate ERW activity.

5.1.3 The generic process boundaries representing an ERW activity at a specific site are defined in figure 2, from mining of the rock up to dispersion of the stored carbon in the environment.

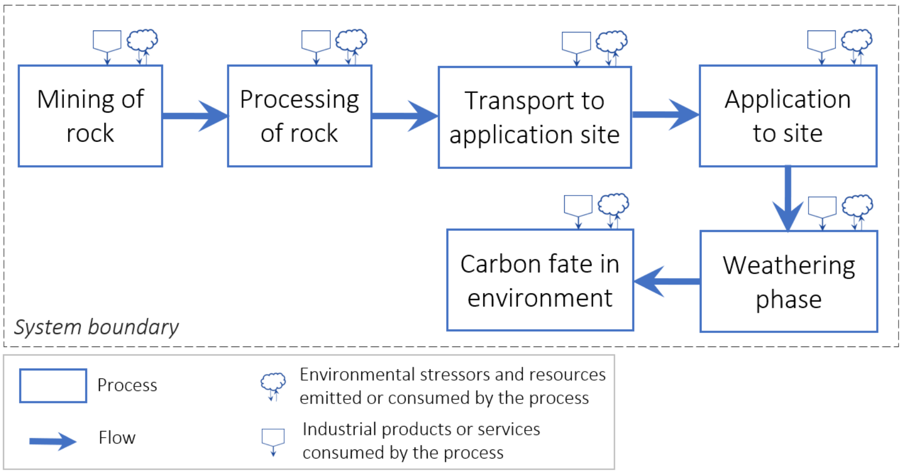

Figure 2: Generic process boundaries for ERW in soils.[18]

5.1.4 Each of the processes included in the system boundaries represents a complete life cycle, for which the full scope of emissions must be included. The processes are briefly described below:

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[18] 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. Note further that "Weathering phase" and "Carbon fate in environment" take place simultaneously, although illustrated sequentially in the flowchart.

- **Mining of rock** refers to all operations required for extracting the rock from the environment for the purpose of ERW activity, including infrastructure requirements, material and energy consumption, as well as waste treatment. In case the weathering rock is a secondary product of another activity, specific LCA procedures apply (see rule 5.1.5). This process terminates with *weathering rock ready for processing at the processing location*.

- **Processing of material** refers to all operations required for processing the material to its final size and granulometry (crushing, grinding, milling) and any other handling, 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*.

- **Transportation to the application site** refers to 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). This terminates with *processed material ready for application at the site*.

- **Application to the site** refers to all operations required for spreading and/or incorporation of the processed material to the site. This includes e.g. machinery and fuel use. This terminates with *processed material applied and incorporated to the soil at the application location*.

- **Weathering phase** refers to the phase starting after application and during which the material is progressively weathered, leading to carbon capture and storage, over the weathering time. This process includes in particular activities required for monitoring, such as travel to site, sampling, analysis and simulation. This process terminates with *performed monitoring over the weathering time*. In addition, this phase shall also assess so-called **direct land use changes**, i.e. any potential change in soil greenhouse gas emissions (biogenic carbon, methane and dinitrogen monoxide) relative to a non-application baseline (see rule 5.1.7).

- **Carbon fate in the environment** refers to the phase starting after application, and during which the stored carbon is moving in the environment (e.g., bicarbonates and carbonates transport to groundwaters, rivers and ocean, and erosion). During this phase, there are no direct greenhouse gas emissions related to the ERW activity beside what is already accounted for in the previous phases. However, there is in this phase potential risk for re-emission of carbon dioxide, through various processes (e.g. pedogenic carbonate formation, so-called "degassing" in groundwater and surface water, or long-term oceanic carbonate formation). The magnitude of re-emissions is not yet well understood [34], and is likely to vary between ERW activities due to different properties of the application site and the receiving water catchments. Re-emissions must be explicitly addressed and quantified in the quantification of CORCs (see section 6).

5.1.5 In case the weathering material is a **waste or secondary product** of another process, it is recommended to apply a cut-off approach[19] for waste, recycled, and secondary products. In other words, the mining or extraction of the weathering material can be considered as "burden-free" (null impact). However, any other operation specifically

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[19] Description of the cut-off system model is available on the website of the ecoinvent life cycle database: System Models

applied to the weathering material must be accounted for (e.g. additional grinding, storage, handling, transport).

5.1.6 In case **co-products** are generated as part of the ERW activity, this may lead to a multi-functionality issue. The LCA shall in that case precisely identify the co-products, quantify their flows, and argue for an appropriate way of handling the multi-functionality issue. The two possible approaches for solving a multi-functionality issue, in the context of CORCs, are i) allocation of burdens between the co-products, and ii) cut-off approach (i.e. neglecting the co-products). The second approach is deemed more conservative and is simpler to implement.

5.1.7 Impact from **direct land use change (dLUC)** refers here to a change in soil greenhouse gas emissions (biogenic carbon, methane and dinitrogen monoxide), after application of weathering material relative to a non-application baseline. Knowledge on dLUC induced by ERW is limited and likely to be dependent on soil properties and management practices. Precise quantification of dLUC induced by ERW would usually require on-site measurements over multiple-years. In the LCA, these emissions shall be estimated with best knowledge available: if dLUC leads to increased emissions, then it must be included in the quantification of CORCs; if dLUC leads to decreased emissions, then dLUC must not be included in the quantification of CORCs, but can be presented as co-benefits of the activity.[20]

5.1.8 For transparency and interpretability, the **LCA results** shall be grouped per life cycle stages (as defined in figure 2), per sub-stages (as fit for each ERW activity), and per greenhouse gases (i.e. total emissions in tCO2e as well as the contributions of CO_2, CH_4, N_2O, and other greenhouse gases). In addition, attention must be given to not aggregate emissions (positive sign) and removals (negative sign) within one group, as it hinders interpretation. Such details in an LCA report must be provided via stacked bar charts and associated tables.

5.2 Spatial and time boundaries

In addition to the process boundaries above, the spatial and time boundaries of the project or activity must be defined in the LCA.

5.2.1 The CO_2 Removal Supplier shall specify the following spatial boundaries of the ERW activity in the LCA:

- Mine location: the origin of the rock or waste must be specified.
- Processing facility: the site(s) of processing of the material must be specified.
- Application sites: the area and the geolocation of the application sites must be specified. Ideally, a map or a geospatial vector data (shapefile) shall be provided.
- Carbon fate: the catchment in which the stored carbon is likely to evolve shall be specified (soil, groundwater, watershed, rivers, ocean entry point, aquifer).

5.2.2 The CO_2 Removal Supplier shall specify the following time boundaries of the ERW activity in the LCA:

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[20] The reasons for handling dLUC differently from other emissions are: i) they constitute an unresolved issue in life cycle assessment theory, ii) they require an allocation time frame for stock changes, which is usually set to 20 years, but which would have a conflicting interpretation with the guaranteed storage duration of CORCs; iii) the need for the assessment to be conservative.

- For a given project, the timing of each process is to be specified. From rock mining to soil application, all processes can be seen as happening within a year and a date (year-month-day) is an acceptable description of the timing of the activity.
- However, from the day of soil application, the weathering process is expected to take multiple years. A conservative estimate of the time needed for reaching various thresholds of weathering of the material must be given (see rule 8.2.1). This can be achieved by providing a curve representing expected weathering completion (in %) over time (in years).
- Likewise, carbon captured in the form of dissolved bicarbonate (and to a lower extent, mineral carbonate) is expected to move in the environment. The time scales of these movements shall be estimated (order of magnitude).

5.3 Relevance of leakage for enhanced weathering

Leakage, also called **economic leakage**, describes the risk of affecting greenhouse gas emissions and removals outside of the system boundaries of the project, but resulting from the implementation of the project. Economic leakage is likely to occur when a CDR project affects the supply of a given product or service, while the demand for this product or service still exists. The term “economic leakage” is similar to the LCA notions of “alternative use”, “substitution” or “system expansion” in change-oriented (comparative, or consequential) LCA studies. Economic leakage is distinct from physical leakage, also known as reversal or re-emissions, which occurs when carbon that is stored throughout the course of a carbon removal project is released back into the atmosphere.

5.3.1 In the context of enhanced weathering, **economic leakage** may occur, primarily, if the weathering material (whether a primary product or a burden-free co-product) was already used to deliver another product or service, and thereby possibly entail the extraction of additional primary material, if demand persists. In that case, the LCA shall include primary material extraction.

6

Quantification of CO_2 Removal Certificates (CORCs)

6.1 General principles

In general, a CORC represents net 1 tCO_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 3) 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.

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

Description	Net amount of CO_2 equivalents removed by the applied weathering material.	Gross amount of CO_2 stored via weathering of the applied rock.	Total life cycle emissions arising from the whole supply chain of the ERW activity.	Total GHG emissions due to negative economic leakage.	Total re-emissions of initially sequestered CO_2
Units	Tonnes of CO_2e	Tonnes of CO_2	Tonnes of CO_2e	Tonnes of CO_2e	Tonnes of CO_2e

Figure 3: The CORC calculation equation.

6.2 Requirements for robust quantification of carbon removal and net-negativity

6.2.1 Continued in-field measurements are required from the CO_2 Removal Supplier throughout the lifetime of the project in order to quantify the amount of CO_2 sequestered.

6.2.2 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.

6.2.3 The CO_2 Removal Supplier shall ensure that any instruments used for data collection are in place and adequately calibrated at all times. The data records shall be kept in a reliable data system.

6.2.4 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 the site-specific modeling of the weathering process.

6.2.5 Based on the results of an LCA analysis and a scientifically justified estimation of the expected carbon removal over time (see rule 8.2.1), 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.

6.3 Overall equation

6.3.1 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 also figure 3 for an illustration):

$$\text{CORCs} = C_{\text{stored}} - E_{\text{project}} - E_{\text{leakage}} - E_{\text{loss}} \tag{10}$$

Variable	Description	Unit
CORCs	Net amount of CO_2 equivalents removed by the enhanced weathering activity.	tCO_2e
C_{stored}	Gross amount of CO_2 stored via weathering of the applied rock. Further requirements on the calculation of this term are given in section 6.4.	tCO_2
E_{project}	Total life cycle emissions arising from the whole supply chain of the enhanced weathering activity. Further requirements on the calculation of this term are given in section 6.5.	tCO_2e
E_{leakage}	Total GHG emissions due to negative economic leakage resulting from the enhanced rock weathering activity. Further requirements on the calculation of this term are given in section 6.6.	tCO_2e
E_{loss}	Total re-emissions or losses of the sequestered CO_2 as a result of subsequent chemical reactions in the environment following the initial weathering. Further requirements on the calculation of this term are given in section 6.7.	tCO_2e

6.4 Carbon dioxide stored (C_{stored})

The term C_{stored} describes the gross amount of carbon dioxide sequestered during the monitoring period through weathering of the applied material, including generation of *carbonate and bicarbonate ions* and *potential precipitation of solid carbonate minerals*.

6.4.1 The CO_2 Removal Supplier shall submit their approach for quantification of C_{stored} for consideration by the Issuing Body as further detailed in subrules (a)–(c).

(a) The quantification approach shall include the determination of C_{stored} based on solid or aqueous phase measurements from in-field soil or water samples, as further outlined in subsections Total alkalinity, and Concentration of major cations of section 7.3.

(b) The quantification of C_{stored} shall be based on measurement of weathering signals relative to control site measurements. The control sites shall be representative of the Production Facility at least in terms of pH, soil texture, and climate conditions, as well as statistically significant in terms of sample count and/or total area.

(c) The Issuing Body shall critically analyze the submitted approach and determine the acceptability and validity thereof based on the requirements of this methodology, and other Puro Standard requirements. The verification of the eligibility of the submitted quantification approach for CORC issuance is made by the Auditor during the Production Facility or Output Audit.

6.5 Project emissions (E_{project})

The term E_{project} must be derived from a life cycle assessment (LCA) of the ERW activity, according to the system boundaries defined in section 5 of this methodology. In particular:

- The LCA should include all types of greenhouse gases, characterized using Global Warming Potentials (GWP) with a 100-year time horizon.
- For any activity included in the life cycle inventory, a full scope of emissions must be accounted for, including all life cycle stages (manufacturing, use, maintenance and disposal) of the processes involved.[21] Therefore, attention must be given when selecting emission factors: emission factors for LCA (usually available in LCA databases) are not the same as emission factors for greenhouse gas inventories (inventory emission factors usually do not include a full scope of emissions).
- In the case of a multifunctional process (i.e. another useful product is generated alongside with carbon removal), a conservative handling of the multifunctionality issue is to fully allocate the burdens to the carbon removal, in this case the ERW activity, and to consider the co-product as "burden-free". Alternatively, the burdens may be allocated between the two products., However, this choice must be adequately motivated and the choice of allocation factors must be explained and justified in the LCA report.
- From a generic LCA performed for one Production Facility and selected application sites, the value of E_{project} can be adjusted for other application sites to reflect differences in, for example, transport distances.

6.5.1 The total life cycle emissions arising from the whole supply chain of the enhanced rock weathering activity (project emissions, E_{project}) shall be calculated as follows.

$$E_{\text{project}} = E_{\text{mining}} + E_{\text{processing}} + E_{\text{transportation}} + E_{\text{application}} + E_{\text{weathering}} + E_{\text{dLUC}} \quad (11)$$

Variable	Description	Unit
E_{project}	Total life cycle emissions arising from the whole supply chain of the enhanced rock weathering activity.	tCO_2e
E_{mining}	Total life cycle emissions arising from the mining of rock (see rule 5.1.4).	tCO_2e

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[21] For instance, use of solar electricity in a process should not be considered to have a null climate impact, rather its climate impact should include the emissions from production, installation, maintenance, and disposal of the panels. Likewise, buildings, equipment and other infrastructure needed for the project must be included. Any material input, energy input, or waste output must be included.

(Continued)

$E_{\text{processing}}$	Total life cycle emissions arising from the processing of weathering material (see rule 5.1.4).	tCO_2e
$E_{\text{transportation}}$	Total life cycle emissions arising from the transportation to the application sites (see rule 5.1.4).	tCO_2e
$E_{\text{application}}$	Total life cycle emissions arising from the application to the site (see rule 5.1.4).	tCO_2e
$E_{\text{weathering}}$	Total life cycle emissions arising from the weathering phase (see rule 5.1.4).	tCO_2e
E_{dLUC}	Total direct land use change emissions associated with the enhanced rock weathering activity (see rule 5.1.7).	tCO_2e

6.5.2 The CO_2 Removal Supplier shall quantify the project emissions (E_{project}) based on a life cycle assessment of the enhanced rock weathering activity, according to the requirements and system boundaries defined in section 5 of this methodology.

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

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

6.6 Economic leakage (E_{leakage})

6.6.1 The CO_2 Removal Supplier shall quantify the total GHG emissions due to negative economic leakage (E_{leakage}) based on an assessment of leakage due to the enhanced weathering activity, in accordance with the requirements defined in section 5.3 of this methodology.

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

6.7 Losses (E_{loss})

6.7.1 The CO_2 Removal Supplier shall quantify and account for all loss (re-emission) pathways. For the purposes of this methodology, a loss pathway is defined as any biogeochemical event or process in the environment following the initial CO_2 sequestration through chemical weathering of the applied feedstock, which results or can reasonably be expected to result in a portion of the sequestered carbon being either released back to the atmosphere, or converted into a form in which the carbon can no longer be considered permanently stored.[22] In particular, common loss pathways associated with enhanced rock weathering include:

- Neutralization of acids other than carbonic acid (strong acid weathering).[23]

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[22] Note that this definition applies to re-emission pathways known or assumed *a priori*, and which therefore need to be accounted for at the time of CORC issuance. Previously unknown or unanticipated re-emissions after issuance of CORCs are termed *reversals*, and are accounted for via a procedure described in the Puro Standard general rules.

[23] In addition to carbonic acid, there are numerous other sources of acidity (i.e protons, H^+) in soil solution that might break down minerals in chemical weathering reactions, resultant for example from natural metal hydrolysis of Al^{3+} and Fe^{3+}, and/or from humic and fulvic acid interactions with water molecules. The excess application of

- Plant uptake of major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}).
- Secondary mineral formation (e.g. precipitation of pedogenic carbonates).
- Losses from surface water systems (e.g. rivers, lakes).
- Losses from marine systems (e.g. seas, oceans).

For the first item, note that while strong acid weathering can lead to direct CO_2 emissions (e.g. in the case of carbonate-containing minerals), it can also prevent CO_2 sequestration from occuring in the first place (i.e. dissolve the weathering material without contributing to CO_2 removal—an aspect that must be considered e.g. in quantification approaches based on monitoring of the flux of major cations). For the purposes of this methodology, strong acid weathering is understood in this wider sense.

6.7.2 The total greenhouse gas emissions due to loss pathways (E_{loss}) shall be calculated as follows.

$$E_{\text{loss}} = \sum_{i \in S} \text{mCO}_2\text{e}_i \tag{12}$$

Variable	Description	Unit
E_{loss}	Total losses of the sequestered CO_2 as a result of subsequent chemical reactions in the environment following the initial weathering.	tCO_2e
mCO_2e_i	Total mass of GHGs emitted from loss pathway i.	tCO_2e
i	Summation index (an element in the set of loss pathways S)	unitless
S	The set of relevant loss pathways (e.g. plant uptake of cations, precipitation of secondary minerals, losses from surface water and marine systems).	unitless

6.7.3 The CO_2 Removal Supplier shall quantify the total amount of CO_2 released from each loss pathway (mCO_2e_i, see rule 6.7.2) through measurement or conservative estimation as further detailed in subrules (a)–(g).

(a) The CO_2 Removal Supplier shall identify all relevant loss pathways (S, see rule 6.7.2). The set of relevant loss pathways shall at least include:

- Neutralization of acids other than carbonic acid (strong acid weathering).
- Plant uptake of major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}).
- Precipitation of secondary pedogenic carbonates.
- Losses from surface water systems (e.g. rivers, lakes).
- Losses from marine systems (e.g. seas, oceans).

The CO_2 Removal Supplier shall quantify the total CO_2 released from each identified loss pathway as further detailed in subrules (b)–(g).

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nitrogen fertilizers and the formation of excess phenolic acids can also result in soil acidification, which is why care should be taken when planning to add weathering materials to over-fertilized soils. Therefore, a well known history of the application sites is recommended.

(b) For the pathway **neutralization of acids other than carbonic acid**, the CO_2 Removal Supplier shall quantify the value of mCO_2e_i through any of the following means:

- Direct measurement the concentrations of major anions in the soil porewaters (e.g. via ion chromatography), combined with an estimate of the total volume of water infiltrated into the soil. 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 land management practices and the weathering material utilized.
- A conservative estimation following the approach outlined in [35] for determining the proportion of weathering by sources of acidity other than carbonic acid via a calculation of the carbonate system speciation based on soil pH and pCO_2 (or, in general, any two parameters of the carbonic acid equilibrium system, such as total alkalinity and DIC, from which pH and pCO_2 may be determined).
- Another method of conservative estimation approved by the Issuing Body. To utilize this method, the CO_2 Removal Supplier shall provide a detailed calculation of the value of mCO_2e_i, combined with evidence to support any assumptions made.[24] The Issuing Body reserves the right to accept or reject the quantification approach based on the evidence presented by the CO_2 Removal Supplier.

(c) For the pathway **plant uptake of major cations**, the value $mCO_2e_i = 0\,tCO_2e$ shall be utilized provided that *at least one* of the following conditions is fulfilled:

- The effect of plant uptake of major cations is already implicitly accounted for due to the specific quantification approach utilized by the CO_2 Removal Supplier (such as approaches based on measuring the alkalinity flux at the base of the soil profile e.g. via monitoring of tile drainage, deep lysimeters below the maximum rooting depth, or catchment drainage waters).
- No crops of any type are being harvested from the Production Facility (i.e. no significant amounts of plant biomass is being regularly removed from any of the application sites).

In case none of the above conditions are fulfilled, the CO_2 Removal Supplier *should* quantify the value of mCO_2e_i through direct measurement of the total base cation content of harvested plant biomass, coupled with an estimate of the total plant biomass removed from the field, and comparable measurements on control plots (to identify the baseline plant cation uptake). However, where the direct measurement of plant uptake of major cations is unfeasible or impossible, a conservative estimation of 5 % of of the value of C_{stored} shall be utilized.

(d) For the pathway **precipitation of secondary pedogenic carbonates**, the value

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[24] For example, if the CO_2 Removal supplier can produce evidence to support the assumption that nitric acid from use of fertilizers is the only significant source of non-carbonic acid weathering, a quantification of strong acid weathering could be derived from documented fertilizer application rates coupled with measurements or estimations of nitrogen use efficiency.

$mCO_2e_i = 0\,tCO_2e$ shall be utilized provided that the effect of precipitation of secondary pedogenic carbonates is already implicitly accounted for due to the specific quantification approach utilized by the CO_2 Removal Supplier (such as approaches based on measuring the alkalinity flux at the base of the soil profile e.g. via monitoring of tile drainage, deep lysimeters, or catchment drainage waters). Otherwise, the CO_2 Removal Supplier shall quantify the value of mCO_2e_i through direct measurements of the soil inorganic carbon stocks of the Production Facility (e.g. via calcimetry), coupled with comparable measurements on control plots (to identify the baseline changes in soil inorganic carbon stocks).

(e) For the pathway **losses from surface water systems**, as a conservative estimation, the value of mCO_2e_i shall equal 5 % of the value of C_{stored} (see [36]).

(f) For the pathway **losses from marine systems**, as a conservative estimation, the value of mCO_2e_i shall equal 10 % of the value of C_{stored} (see [37]).

(g) For any other potential loss pathways identified in accordance with subrule (a), besides those within the purview of subrules (b)–(f), the CO_2 Removal Supplier shall provide a detailed description of the identified pathway and the method of quantification.

7

Data collection and monitoring

7.1 General monitoring guidelines

Assessing the realistic potential of enhanced weathering as a method for carbon dioxide removal is hindered by the fact that to date (Oct 2024), despite laboratory, mesocosm, and field trial studies, a comprehensive experimental body of data concerning weathering rates in field conditions is still largely missing. Even though the pool of available in-field experiments for model validation is rather limited, the examples in [10, 11, 15, 38–48] could be considered for the past decade.

Various methods of in-situ validation of weathering models have been suggested in the literature, but as of yet (Oct 2024) the quantification of C_{stored} has not reached a scientific consensus, nor has it been included in IPCC's greenhouse gas inventory guidelines (last refined in 2019) [49].

The list of weathering signals in section 7.3 provides an overview of experimentally measurable quantities (such as total alkalinity or total inorganic carbon) indicative of weathering reactions taking place in the soil and utilized in the quantification of CO_2 sequestered.

It is to be noted that the methods presented possess varying degrees of accuracy and predicting power, and thus need to be *combined* until an accurate validation approach has a proven track record. It is especially important that the validation approach is able to quantify the weathering *due to carbonic acid* (and hence the CDR), as e.g. strong acids in the soil could affect weathering rates without leading to CO_2 sequestration. The validation approach should also include controls (i.e. measurements on soil without ERW) since weathering signals are often relative.

In-situ (in-field) carbonate sequestration is difficult to measure, but there are several supplementary parameters or proxies that can be used to follow the impacts of enhanced weathering. These can be measured in the soil, in the water (e.g. soil pore water, underground water, leachates, surface waters), and at the surface using gas-flux measurement devices.

7.2 Guidelines for sampling

Soil sampling

A proper sampling procedure is crucial to ensure representative and accurate measurements resulting in detectable weathering signals.

Soil sample collection

- **Option 1. Sample collection from homogeneous plots.**
  This option is recommended for smaller application sites that have similar historical background. Divide the total application area into homogeneous plots, i.e. into areas with similar:
    - soil (e.g. with the help of available public information such as GIS maps, information gathered from the stakeholders, and visual observation);
    - topography (e.g. use available cartography maps and visual observation);

    - vegetation (e.g. use information provided by stakeholders); and
    - history of use (e.g. use information provided by stakeholders).

  The last point (similar history of use) is particularly important because the same area that has been more intensely cultivated will present different chemical behavior (e.g. due to the addition of high chemical fertilizer loads).

  Collect approximately 15 subsamples from each homogeneous plot, which should be mixed to form a single composite sample that is then sent to the laboratory.

- **Option 2. Georeferenced sample collection.**
  This option is recommended when there is knowledge that the application site is very heterogeneous or has a very large area.

  Delimit the area by collecting geographic coordinates. Based on a georeferenced map of the application site, the application area should be divided into smaller cells that vary from one to several hectares. Subsamples should be collected within a radius of 5–15 m from the georeferenced point.

Soil sampling depth

The sampling depth should be at least between 0–20 cm. Sampling at subdivisions of this depth can also be used when suspecting that weathering signals will be found at different depths (e.g. 0–10 cm and 10–20 cm or even smaller: 0–5 cm, 5–10 cm, and 10–20 cm). Subdivisions in depth are recommended for soils that are not tilled, as higher vertical and horizontal variability is expected in those areas.

Water sampling

Vacuum tools

The most widely used tools for soil pore water collection are rhizon samplers and porous ceramic cups. 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 each tool.

The porosity of the samplers will dictate what parts of the soil pore water will be collected. Rhizons have typically sub-micron pore sizes, having the advantage of avoiding a filtering step before measurements (if working properly). However, having such a small permeable tip might lead to selective sampling due to adsorption forces in the soil.

Ceramic cups are much more complex and come in many different sizes. They can collect higher pore water volumes (few hundreds of millimeters) in comparison to the rhizons that can only collect 20–40 mL of water pulled into syringes. As a ceramic cup tip is typically composed of a ceramic material that has higher porosity (on the micron scale) compared to rhizon samplers, samples need to be filtered before most measurements (0.45 µm filters are recommended to eliminate microorganism and solid particles).

Passive tools

Lysimeters of many shapes and sizes have been developed for various agronomic and ERW studies to measure leachate soil water. These devices typically 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. Nevertheless, lysimeter samples can be quite effective in measuring leached alkalinity.

Variabilities due to design and size of the lysimeter, as well as its position in the field should be taken into account during data interpretation. Furthermore, attention should also be paid to how the soil is inserted in the lysimeter, as homogenized soil and intact soil will require different interpretations. Samples collected in lysimeters require filtering before measurements (0.45 µm filters are recommended to eliminate microorganism and solid particles).

7.3 Guidelines for measurements

Total alkalinity

Description:

Total alkalinity refers to the total concentration of *alkaline species* in the soil pore waters, and is a measure of the capacity of water to resist acidification. In enhanced weathering, the dissolution of minerals by carbonic acid leads to the release of cations into the soil, which increases total alkalinity and draws down CO_2 into dissolved inorganic carbon (e.g. $HCO_3{}^-$). An increase in total alkalinity in the soil pore waters where the weathering material was applied, relative to the soil without treatment, indicates that weathering is taking place. The alkalinity flux, i.e. the flux of ions into solution during mineral dissolution is the driver for CO_2 removal and a key measure for the rate of enhanced weathering.

Pros:

The measurement of total alkalinity is economical and straightforward, and can be performed via titration (or less accurately by colorimetry: observing a color change on a conversion chart).

Cons:

The collection of samples and the subsequent laboratory analysis can be cumbersome and offers only limited resolution in space and time. Reliable evaluations of the weathering reactions would require rather frequent (e.g. monthly) analyses of samples in different locations over several years, and specialized equipment to collect the water samples (e.g. lysimeters).

Concentration of major cations

Description:

The concentration of major cations refers to the total concentrations of the primary positively charged ions (e.g. Ca^{2+}, Mg^{2+}, Na^+, and K^+) dissolved into the soil pore water and/or sorbed to the soil and are typically measured by using spectroscopic methods (e.g. ICP-OES, ICP-AES, ICP-MS). In ERW, the dissolving minerals release these cations into the soil where they contribute to the electrical conductivity and alkalinity. When cations stay sorbed in the soil, an increase in the concentrations of major cations in the soil is an indication that weathering is taking place. However, leachate mechanisms can be occurring at the same time. Thus, a control site for measuring natural weathering and leachate processes (among others) is needed.

The budget of these major cations, including proof of both their initial mineral addition and subsequent loss, is a quantity valid for estimating alkalinity fluxes into the subsurface. This can be experimentally gauged e.g. by measuring changes in the total amount of these metal cations in a specific soil sample relative to the concentration of an immobile trace element (ITE). An increase in ITEs as introduced by the applied mineral (e.g. Ti, Cr(III), rare earth elements) alongside the loss of base cations from the same soil sample quantifies both the extent of weathering as well as the alkalinity flux into the subsoil and can thus be utilized for CDR verification [50].

Pros:

The laboratory analysis to measure major cations by e.g. inductively coupled plasma mass spectrometry (ICP-MS) is fast, sensitive and selective to the specific ionic species. ICP-MS can be used to measure multiple elements with a wide range of concentrations. Estimation of the initial addition and subsequent loss of the major cations—achieved e.g. through the monitoring of immobile trace elements—provides empirical evidence that a specific mineral has been applied, and the rate of its application. The estimation of initial mineral addition, together with evidence of loss of the major cations it possessed, can be considered strong proof of the CDR flux as long as other ion loss mechanisms are accounted for (see below).

Cons:

Simply measuring the concentration of major cations has limitations similar to electrical conductivity measurements (see subsection Soil electrical conductivity), whereas measuring the alkalinity flux through the loss of these cations has slightly different limitations. Some ITEs can be contained in e.g. fertilizers (such as rock phosphate), resulting in an overestimate of mineral additions. Furthermore, some ITEs are not perfectly immobile and may underestimate initial mineral additions. Losses through processes that do not result in permanent CDR (e.g. plant uptake, or pairing with non-bicarbonate anions) must be constrained by experimentation. Samples with high and variable solids content can be challenging to analyze by ICP-MS due to interferences from the sample matrix.

Total inorganic carbon

Description:

Total inorganic carbon (TIC) refers to the total amount of inorganic carbon species present in the soil, mainly in the form of simple compounds such as carbonates, bicarbonates, carbonic acid and carbon dioxide. In ERW, the dissolution of the weathering material leads to e.g. bicarbonate ions (HCO_3^-) being released into the soil pore waters, which increases the total inorganic carbon content. Precipitation of inorganic carbon through pedogenic carbonate formation has been reported in some pot-based trials and field studies surrounding ERW [41, 51].

Pros:

The determination of total inorganic carbon content is economical and simple, and can be easily performed with e.g. a CN analyzer or various other experimental methods. Commonly, the process involves acidification of the sample with a strong acid (e.g. HCl), which turns the inorganic carbon species to carbon dioxide, and the subsequent quantification of the CO_2 gas formed e.g. by a coulometer or an IR analyzer.

Cons:

Inorganic carbon resulting from enhanced weathering is not necessarily retained in the soil at the application site, as the water soluble species can be transported via runoff waters to streams and ultimately the ocean. Hence, both changes in the TIC of the soil as well as the dissolved inorganic carbon (DIC) of the runoff waters should be considered in order to quantify the total CO_2 sequestration through ERW. However, the quantification of DIC leaching losses is difficult in field conditions, which limits the applicability of the method. Furthermore, the changes in soil TIC following the application of the weathering material might be too small compared to background levels to be easily quantifiable in the field.

pH

Description:

pH refers to the concentration of solvated hydrogen ions in the soil pore waters, and is a measure of their acidity. An increase in pH in the soil where the material was applied, relative to the soil without treatment, indicates that alkaline substances are being released into the soil, which is indicative of mineral dissolution taking place. In ERW, pH is a key factor influencing weathering rates and hence carbon sequestration. For example weathering rates typically increase with decreasing pH, although this relationship differs between minerals. Aside from affecting the dissolution of ions into the soil pore waters, pH also plays a key role in the subsequent reprecipitation reactions. It is worth mentioning that the soil pore water pH as collected by root-imitating equipment (e.g rhizons) and lysimeters will provide different types of data that need to be properly interpreted. Moreover, the measurement of soil pore water pH and the measurement of the agronomic soil pH are also very different types, resulting in different interpretations and conclusions about the application site.

Pros:

The measurement of pH is very simple and economical, does not require complicated machinery, and can be easily performed in field conditions with a portable soil pH meter.

Cons:

Several factors affect soil water pH (besides the carbonic acids, also the presence of humic acids, chemical fertilizers, organic matter, chemical compositions, iron and aluminum redox reactions, etc), and the measurement of pH alone is not sufficient to quantify weathering or CDR.

Soil electrical conductivity

Description:

Soil electrical conductivity (EC) refers to the ability of the soil pore waters to transmit or attenuate electrical current, and is a measure of water-soluble salt. It is mainly determined by the moisture content and ions dissolved in the soil pore water. Amann and Hartmann have outlined an approach to predict CO_2 sequestration using an empirical relationship between electrical conductivity and total alkalinity from lab column experiments and field observations [38]. Measuring EC from a probe or an automatic sensor inserted in the soil is prone to different pros and cons and different result interpretations.

Pros:

Soil electrical conductivity is simple and straightforward to measure in field conditions with a probe, and can be monitored in real time.

Cons:

Several factors affect soil electrical conductivity, including planting, irrigation, land use, and compound fertilizer application. The approach proposed by Amann and Hartmann showed a relationship between electrical conductivity and total alkalinity, but the accuracy of determining total alkalinity from electrical conductivity is currently low, and no generalized equation was derived. The measurement of soil electrical conductivity alone is not sufficient to quantify weathering or CDR.

Isotope ratios

Description:

Isotope ratio refers to the relative amounts of different isotopes (atoms of the same chemical species but with different numbers of neutrons in their nuclei) in the soil. Stable (non-radioactive) isotopes have a natural abundance, but some natural processes favor one isotope over another, which can result in the enrichment of one isotope compared to another in e.g. soil, plants, and animals. A change in isotope ratios of relevant elements (e.g. C, alkaline earth metals, trace metals) following the application of weathering material can be used as an indicator of the extent of weathering, the fate of weathering products, and/or the extent of CO_2 sequestration. In particular, Sr and Li isotope ratios can be used to quantify weathering, and O and C isotope ratios can be used to confirm a pedogenic origin for carbonate in soils [44].

Pros:

The isotopic ratios of a sample can be used to determine the origin of certain chemical elements in the sample. In ERW, changes in isotope ratios of the soil can be used as evidence that minerals from the weathering material have dissolved into the soil. Furthermore, isotope analyses can be used to assess the fate and flux of elements dissolved from the weathering material (e.g. whether retained in the soil, taken up by plants or leached to the water, etc.). Laboratory measurements of isotope ratios by e.g. mass spectrometry possess a very high degree of accuracy and specificity.

Cons:

The laboratory work to perform e.g. compound specific isotope analysis via the traditional mass spectrometry approach is delicate and expensive compared to most other methods mentioned, and requires special machinery to perform, although portable devices based on infrared spectroscopy exist e.g. for measurements of C and O isotope ratios. Measurements of isotope ratios alone do not allow the direct quantification of CO_2 sequestered.

7.4 Requirements for experimental monitoring

7.4.1 For issuance of CORCs, the CO_2 Removal Supplier shall perform, at least annually after application, in-field measurements to quantify the amount of CO_2 removed by the enhanced weathering activity. Furthermore, the CO_2 Removal Supplier shall, where necessary, utilize the results of the in-field measurements to update the weathering model, as per the requirements defined in section 8.2.

7.4.2 The CO_2 Removal Supplier shall provide evidence, in the form of laboratory analysis reports of field samples (e.g. results from soil and weathering material analyses) and/or other similar in-field measurement data (e.g. data from measurements conducted directly on-site), that supports the project-specificity of the approach used to quantify the weathering process and the expected carbon removal. This includes, but is not limited to, results from laboratory analyses of the weathering material, amended soil samples, and control soil samples, determining the key properties necessary for the empirical quantification of CO_2 removal, and the design and operation of the weathering model (e.g. rock or mineral elemental and mineralogical composition, particle size, surface area, soil pH, soil texture).

7.4.3 The CO_2 Removal Supplier must prepare a monitoring plan detailing any associated resources, for the time of the monitoring phase (post-application).

   (a) The monitoring plan shall at least cover all aspects related to:

  - Eligibility of the activity (e.g. environmental safeguards in line with risk assessment, effects on crop yields).
  - Quantification of CORCs (e.g. in-field monitoring of weathering, material and soil analyses, climatic data, data for supply-chain emission calculations).

(b) The monitoring plan shall describe the following information for each monitored parameter to the relevant and applicable extent:

  - A description of what information each parameter conveys.
  - The sampling methodology.
  - The temporal and spatial sampling frequencies.
  - The utilized procedures and/or analytical methods.
  - Expected or normal values or value ranges.
  - Representativeness and uncertainties.
  - Quality assurance and quality control measures, including calibration procedures of measurement equipment.
  - Information about any external laboratories and outsourced procedures utilized (names and addresses).

7.4.4 The CO_2 Removal Supplier shall conduct a geochemical assay detailing the composition of the weathering material as further specified in subrules (a) and (b).

(a) The geochemical assay shall at least encompass the following properties:

  - Particle size distribution
  - Chemical oxide composition
  - Mineralogy
  - Major and minor chemical elements.

(b) The geochemical assay shall be conducted at least once per every 5000 t of weathering material applied, and whenever *at least one* of the following conditions is fulfilled:

  - Weathering material is spread to a new Production Facility (i.e. beginning of project).
  - Weathering material is sourced from a new supplier or quarry.

7.4.5 The CO_2 Removal Supplier shall conduct a soil analysis at the Production Facility before the spreading of the weathering material as further specified in subrules (a)–(c).

(a) The soil analysis shall determine the soil type(s) and initial (baseline) physical and chemical characteristics of the Production Facility, including at least the following parameters:

  - Soil texture and composition, including at least the percentage of clay and bulk density for soil type assessment. The further determination of percentages of sand and silt is recommended.
  - Soil pH

- Cation exchange capacity (CEC)
- Soil organic carbon (SOC) content
- Soil inorganic carbon (SIC) content
- Concentration of major base cations (i.e. Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+})
- Potentially toxic elements (PTEs, see section 4.2)

(b) 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.

(c) The CO_2 Removal Supplier shall ensure that the collected soil information is statistically representative of the entire Production Facility. The CO_2 Removal Supplier shall determine an appropriate sampling density based on the site-specific characteristics of the Production facility (such as the types of soils within the Production facility and the underlying spatial variability thereof, typical parameter ranges and variance).

Ideally, a sampling density of 1 sample per hectare of total area of the Production Facility is recommended (see also section 7.2 for further guidelines on sampling).

8

ERW simulation models

8.1 Guidelines for ERW models

Enhanced rock weathering is an inherently slow process that can have a project duration of several years or decades. Therefore, modeling of the CDR potential over time and possible risks associated with ERW is needed in order to ensure efficiency and manage the risks involved in a given project. In addition to experimental monitoring, this methodology requires CO_2 Removal Suppliers to undertake site-specific modeling of their ERW activity (see section 8.2).

Various modeling approaches of different types have been suggested in the literature (see for example [1, 4, 5, 10, 11, 47, 48, 52–57]), but to date (Oct 2024), no scientific consensus exists on the best approach to simulate the enhanced weathering process in the field. As different models can vary significantly with respect to the data required, inputs, outputs, and theoretical approaches, it is important that certain guidelines are issued to steer the simulation process towards reliable results.

The following list includes *suggestions* for properties that would ideally be included in the modeling approach. Although it is unlikely that a given model would explicitly include every single suggestion, an adequate simulation approach will likely contain several of the suggestions mentioned.

Finally, it should be noted that 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.

Theoretical basis

The modeling approach should have a basis in science, and be underpinned by published, peer-reviewed research. The theoretical background should be commonly accepted in the scientific community. The simulation should result from a mechanistic approach (i.e. theory-based rather than statistical predictions based solely on empirical data), data driven dynamics approach, which includes interactions between the rock-soil-plant-atmosphere system.

Suggestions checklist:[25]

- Scientifically justifiable
- Based on published, peer reviewed research
- Commonly accepted theoretical background
- Mechanistic rather than fully empirical
- Data driven

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[25] The suggestions checklist provides a succinct summary of the points discussed within each subsection.

- System dynamic approach (e.g. rock, soil, plant, water, atmosphere all interacting with one another)

Specificity

Only models that are specifically designed to simulate enhanced weathering in the field should be used. Ideally, the model should also be designed to explicitly quantify the CDR associated with the weathering reactions. The model should be designed to accept project specific inputs, and so far as possible, include parameters (e.g. solubility, kinetic and thermodynamic data) measured in conditions relevant to in-field applications.

Suggestions checklist:

- Designed to model ERW
- Project specific inputs
- Optimized for CDR
- Relevant conditions for measured parameters (e.g. in-field vs laboratory)

Parameters

Different modeling approaches can vary significantly in the data required, but the model should at least include thermodynamic and kinetic parameters related to the reactions occurring during chemical weathering such as mineral solubilities and dissolution and precipitation rate constants.

Suggestions checklist:

- Thermodynamic and kinetic parameters:
    - Temperature and partial pressure
    - Mass and density
    - Activities and solubilities
    - Reaction rate constants

Modeled phenomena

Due to the complex nature of enhanced weathering, there are several factors for the model to consider. The model should include, as a minimum, a description of the most relevant biogeochemical processes occurring in the system (e.g. CO_2 dissolution and degassing, the dissolution and precipitation of solid species, chemical reactions, sorption, ion exchange, autotrophic and heterotrophic respiration). Furthermore, the model should include a description of the transportation of fluids and chemical species in the system, such as advection, diffusion, dispersion, the leaching of water through the soil and ideally the ultimate fate of dissolved species (e.g. whether retained in the soil or flushed to the streams and eventually the ocean).

The various chemical reactions occurring during weathering should be modeled via chemical kinetics. Ideally, this would also include factors such as kinetically-controlled reactions and non-equilibrium kinetics. The model should also include a description of effects due to physical size of the mineral particles being spread (e.g. grain size, surface area, roughness, and changes to particle size due to mineral dissolution), as well as any possible secondary effects affecting the dissolution of grains such as fluid supersaturation, clay formation and surface passivation effects.

The modeling approach should include some degree of spatial resolution such that, for example, the depth dependence of moisture, ion concentrations, pH, etc. can be taken into account. The model should also be able to include the most important factors arising from the changes in the environment (such as weathering rates being affected by pH, plants taking up and releasing ions etc.), as well as, ideally, the various other forms of disturbances to the soils, such as mixing of the topsoil due to tilling, bioturbation due to soil surface fauna etc. Finally, if applicable, the model should be able to account for the possible periodic changes in physical or chemical parameters, such as application of more weathering material or changes in e.g. the composition of the weathering material or porosity of the soils.

Suggestions checklist:

- Relevant biogeochemical reactions and processes
    - CO_2 dissolution / evolution
    - Mineral dissolution and precipitation
    - Acid-base and redox reactions
    - Sorption, ion exchange, and surface complexation
    - Soil and plant respiration
- Transport of fluids and chemical species
    - Water leaching
    - Advection, diffusion, dispersion
    - Ultimate fate of dissolved species
- Thermodynamic and kinetic processes:
    - Chemical and phase equilibria
    - Kinetics under non-equilibrium thermodynamics
    - Reaction mechanisms
    - Ion exchange
    - Surface complexation
    - Fluid mechanics
- Particle size effects
    - Grain size distribution
    - Surface area
    - Mass and surface reduction over time
- Secondary effects
    - Clay and other secondary phase formation
    - Passivation of surface sites
- Spatial resolution
    - Depth profiles of concentrations and CO_2 partial pressure
    - Changes in pH or other conditions

- Changes due to environment
  - Uptake/release of ions/chemical species by plants (e.g. humic acids action)
  - pH dependence of weathering rates or chemical reactions
  - Soil texture (e.g. bioturbation by soil surface fauna, tilling)
  - Fungal and bacterial action
- Changes through time
  - Application of material
  - Changes in physical or chemical parameters e.g. weathering material, porosity

Input

The inputs of the model should be at least partially project specific and tailored to the specific weathering material used and environment conditions. The model inputs should include the chemical and mineral composition of the weathering material (e.g. weight mass of each mineral phase, oxide content of each cation, surface area and particle size distribution) as well as data related to the environment such as local climate conditions and properties of the soil itself. The inputs should also be able to quantify the amount of material being spread, and rates of reapplication if relevant.

Suggestions checklist:

- Weathering material composition
  - Mineral composition (weight percentages of each mineral in the weathering material)
  - Cation oxide mass concentrations
  - Surface area
  - Particle size distribution
- Environment data
  - Climate
  - Soil nature, texture, bulk density, and other properties (e.g. pH, %OM, TOC, TIC, CEC)
  - Water flow
- Load of material spread (in $\mathrm{t\,ha^{-1}}$)

Output

The most important property of the model is that it should be able to quantify the CDR taking place in an explicitly time-resolved fashion, such that the model is able to predict the amount of CO_2 captured each year following the application of the weathering material. The model should also be able to output other supporting data, such as concentrations of the relevant chemical species, element mass transfer rates etc.

Suggestions checklist:

- Quantifies time resolved CDR

- Concentrations of relevant chemical species
- Element mass transfer rates / dissolution rates

Uncertainty

In order to adequately quantify the various risks involved in real-world projects, the modeling approach should be able to quantify several types of uncertainties. The model should include sanity checks such that e.g. the theoretical maximum rates of CDR are not surpassed. Furthermore, the model should include checks to ensure internal robustness to avoid e.g. compounding of numerical errors or butterfly effects. The model should include some degree of quantification of the uncertainty of the simulation, both due to uncertainties of the input parameters (e.g. Monte Carlo simulation), as well as with respect to expected performance in the field (e.g. goodness-of-fit indicators, Root Mean Square Error).

Ideally, the model should include the possibility of reducing uncertainty or optimizing performance of CDR. This could be achieved e.g. by identifying the most important contributions to CDR within the model, possible losses in the system, the effect of background weathering reactions etc.

Suggestions checklist:

- Sanity checks (e.g. theoretical maximum)
- Internal robustness (e.g. butterfly effects, numerical instabilities)
- Mathematical evaluation of uncertainty
  - Monte Carlo simulations
  - Goodness-of-fit indicators
  - RMSE evaluation
- Measurement uncertainty
- Possibility to optimize / reduce uncertainties
  - Most important contributors to CDR
  - Possible losses (e.g. CO_2 release by increased microbial respiration)
  - Background weathering or other effects

Validation

In order to ensure a credible and robust ERW methodology, the proper validation of simulation results is paramount. The simulation approach should be transparent, and at least the core components should be publicly available.

Ideally, the modeling approach should be published in a peer-reviewed scientific journal, preferably open-access. The model should be able to predict directly experimentally verifiable weathering signals such as pH, dissolved inorganic carbon and ion concentrations. Furthermore, the models should ideally be calibrated to or at least backed up by data measured in-field in an enhanced weathering setting.

Finally, it is important for the credibility of the methodology that the model be explainable and traceable, i.e. not a convoluted neural network, for example, where the internal decision process is difficult or impossible to explain. It is to be noted that AI models are not inherently bad, and are extensively used today even in cases where the exact inner workings of the models are not completely understood. Ultimately, the question often boils down to the superior efficiency of e.g. neural networks or other complex AI models in performing demanding tasks, but in cases where comparable accuracy can be achieved with explainable models, these latter should be preferred to ensure that the right decisions are being made for the right reasons.

Suggestions checklist:

- Publicly available
- Published in a peer-reviewed scientific journal
- Experimentally verifiable predictions
- Traceable / explainable (not only a black box AI)
- Backed up by experimental EWR data

8.2 Requirements for ERW simulation models

8.2.1 The CO_2 Removal Supplier shall provide 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 duration of the project (project time horizon).

(a) The estimation shall be based on a site-specific simulation model of the weathering process, which shall be completed by the time of the Facility Audit. However, during the pre-Audit stage, the CO_2 Removal Supplier may utilize other scientifically justified (initial) estimations of future weathering in lieu of a full site-specific simulation, such as an extrapolation based on experimentally determined weathering rates from measurements conducted in a relevant setting (e.g. from a previous pilot project).

(b) The estimation shall take into account the specific characteristics of both the weathering material and the application sites including, but not limited to, soil and climate conditions.[26]

(c) The estimation shall be periodically updated based on results of the in-field monitoring and measurement activities conducted by the CO_2 Removal Supplier.

8.2.2 The CO_2 Removal Supplier shall provide initial simulation results for the specific ERW activity considered, quantifying the expected carbon removal over time, as well as other relevant model outputs and weathering signals. In case the CO_2 Removal Supplier has utilized other scientifically justified initial estimations of weathering in accordance with rule 8.2.1, the CO_2 Removal Supplier shall further provide a comparative analysis of the results of the initial estimations and weathering model outputs to identify any significant differences in the expected carbon removal between the estimations.

8.2.3 **Project specificity**: the simulation shall capture site-specific project parameters, for instance the properties of the application sites, rock mineralogy, specific surface area, the local climate such as rainfall, temperature and local hydrology.

8.2.4 **Dynamic simulation**: the simulation shall have an explicit time dimension showing the temporal changes of carbon storage at each year.

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[26] Given that a Production Facility may be composed of several application sites with different soil types, estimations for each scenario (weathering material + climate + soil type) should be presented. Different soil types include loam soil, clay soil, sandy soil, silty soil, chalk soil, and peat soil.

8.2.5 **Uncertainty estimation**: the simulation shall quantify or estimate the uncertainty on its outputs. Specifically, the CO_2 Removal Supplier must provide explicit quantification of the error induced by spatial and temporal heterogeneity in both the simulation result and in the site-specific empirical measurements being used to constrain and drive the simulation.

8.2.6 **Empirical inputs and monitoring**: the simulation shall have as input empirical data from on-site measurements, possibly supplemented by other measurements derived from public datasets (e.g. national environmental monitoring and meteorological programs). All projects must conduct empirical monitoring at the application sites, and a detailed monitoring plan must be made available (see section 7.4).

8.2.7 **Simulation validation**: the simulation must be validated by site-specific empirical data or data that captures these specifics from a regionalised perspective. The CO_2 Removal Supplier must 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 (see also section 7.4).

8.2.8 **Simulation publication and availability**: the use of a peer-reviewed, open-source model, (e.g. published in a scientific journal) is highly encouraged. Any computer code and datasets behind the simulation shall, to the extent possible, also be available in repositories.

8.2.9 **Simulation assumptions and references**: any assumptions made in the simulation shall be critically discussed, and their validity conditions shall be clearly expressed. All external references used in the simulation shall be clearly indicated and explained.

8.3 Supplementary examples of simulation approaches

For ERW in soils under real field conditions, the quantification of the term C_{stored} is associated with uncertainties, and benefits from both simulations and monitoring with in-situ measurements for validation of simulations.

An ERW simulation 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. Simulation 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 7). Below, some examples of commonly utilized ERW simulation models are presented.

The Kelland model and simulation approach

The Kelland model (see figure 4) is a one-dimensional (1D) soil geochemical reactive transport soil process model to estimate CO_2 removal for basalt weathering over multi-decadal timescales. The model was published in open-access peer-reviewed journals: first in [10], and further developed in [55] and [11]. The model has been initially validated using soil pot trial experimental data [10, 11], and further model validation is in progress as new data becomes available.

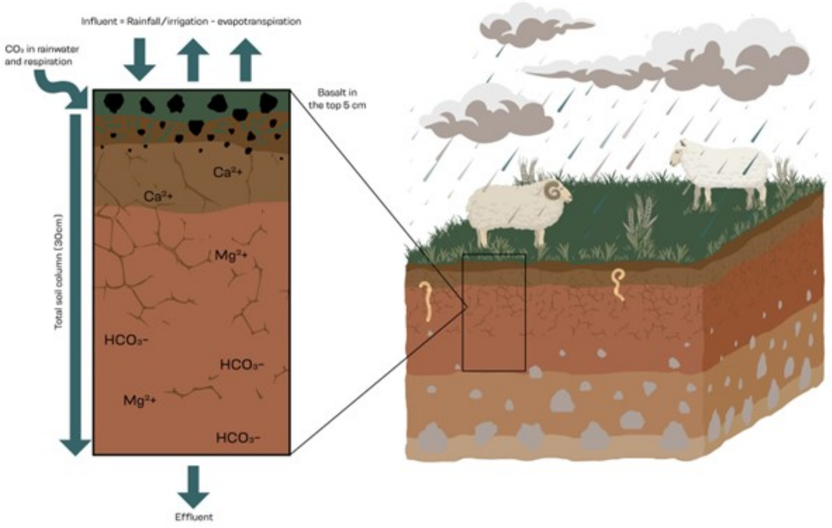

Figure 4: Visualization of the Kelland model. Image courtesy of UNDO Carbon ltd.

Assumptions

The model assumes the downward migration of rainwater or irrigation water through a 30 cm soil profile with basalt mixed into the top 5 cm.

Inputs

The main model inputs are:

- Basalt mineralogy, particle size, surface area, and density of application.
- Site-specific soil chemical and physical parameters.
- High-resolution, long-term weather data (precipitation, air temperature).

The model also uses various experimentally derived kinetic and thermodynamic data for simulating the biogeochemical processes outlined below.

Processes

The model accounts for different biogeochemical processes including:

- Dissolution and precipitation of primary and secondary minerals.
- Adsorption and desorption of ions onto mineral and organic carbon surfaces.
- Transport of fluid and ions as pore water solutions.
- Transport of CO_2 dissolved in rainwater or irrigation water, as well as CO_2 from respiration of organic matter within the soil profile.
- Progressive reduction in silicate mineral reactive surface area with dissolution.

Outputs

The model outputs are evolutions over time of the pH in the soil pore water, chemical element release rates due to weathering (e.g. Ca^{2+}, Mg^{2+}), as well as bicarbonate ($HCO_3{}^-$) and carbonate ($CO_3{}^-$). Carbon dioxide sequestration is estimated by balancing the chemical equations with $HCO_3{}^-$, which is ultimately precipitated in the oceans as calcium carbonate ($CaCO_3$). From this data, the model generates a 'weathering curve' that provides an estimation of the cumulative tonnes of CO_2 sequestered per hectare of land over time. The model also has the potential to simulate the potential for the precipitation of calcium carbonate through thermodynamic equilibrium.

The SCEPTER model and simulation approach

The Lithos modeling framework is a suite of coupled models that predict CO_2 capture in soils, transport of weathering products to the oceans, and the storage of captured carbon in the oceans on decadal to thousand-year time scales (see figure 5).

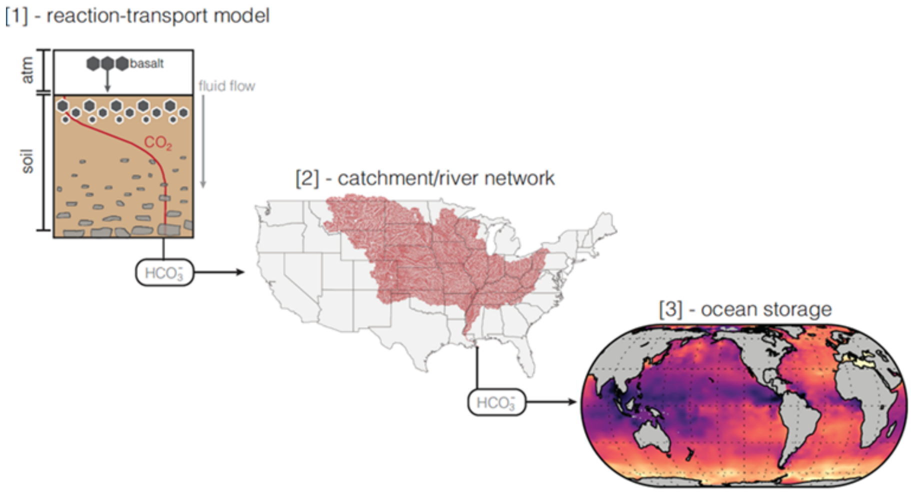

Figure 5: Overview of the three components of the Lithos enhanced weathering modeling framework that allows for estimates of carbon capture during weathering and the amount of carbon storage in rivers and the oceans over a given timeframe.

SCEPTER

The first component of the framework is a one-dimensional geochemical reactive transport model designed to replicate enhanced rock weathering in soils. This model is known as SCEPTER, which stands for Soil Cycles of Elements simulator for Predicting TERrestrial regulation of greenhouse gases [58]. The model was initially validated through comparison to soil chemistry in a range of in-field settings with different soil types and organic matter concentrations [58].

Assumptions

The model assumes transport of rainwater (or irrigation water) through a soil profile via advection and diffusion and that mineral dissolution and precipitation are controlled by geochemical thermodynamics and kinetics. Grain sizes, porosity, and permeability are all dynamic.

Inputs

The main model inputs are:

- Rock and mineral feedstock application rates and the physical characteristics (particle size distribution, surface area, mineralogy).
- Climatological boundary conditions (such as surface temperature, water infiltration rate and soil water content).
- An initial soil mineralogy and organic carbon concentration based on either soil type and/or the chemical composition of the soil.

- Kinetic and thermodynamic data for a reaction network that couples 39 mineral phases and different classes of organic matter, 58 aqueous (dissolved) species, and 4 gas species.
- Time varying soil mixing regimes (such as natural bioturbation or tilling).
- Crop type and fertilization protocol.

Processes

The model accounts for background and enhanced weathering and other biogeochemical processes including:

- Dissolution and formation of mineral phases.
- Dissolved ion transport.
- Plant uptake and sorption.
- CO_2 introduction into the soil profile through gas phase transport and organic carbon respiration.
- Dynamic re-equilibration of the carbonic acid system.
- Organic acid production and destruction.
- Grain-size driven changes in feedstock surface area as weathering proceeds.
- Modulation of soil carbonate chemistry by initial ('residual' acidity) and sorbed cations.

Outputs

The model outputs are time-dependent estimates of evolving soil chemistry, including changes in carbonate chemistry and changes in cation concentrations, along with integrated carbon dioxide removal (CDR) over any timeframe. Given that the model is run as an open system, carbon fluxes—in dissolved and gas forms—are also continuously calculated. The modeled dissolved components are then exported into the second stage of the model framework (see below).

Dynamic river network and cGENIE

The second and third components of the Lithos framework are a dynamic river network coupled to an ocean carbon cycle model from the global Earth system model cGENIE [59, 60]. These models track the products of enhanced weathering in surface waters and in the oceans on a decadal to thousand-year time scale. The machine learning component of the river network is validated using 25 % of empirical data, and the framework is able to predict over 80 % of the data for all chemical species of interest. cGENIE has been extensively validated based on comparison to modern oceanographic data.

Assumptions

The models assume export of water from the weathering zone into surface waters after passing through a soil column, and that the river waters enter into a homogenous surface ocean box at a fixed location.

Inputs

The main model inputs are:

- A high-resolution digital elevation model that is used to specify the catchment for the site of enhanced weathering.

- Extensive river chemistry data (> 106 individual data points) and high-resolution climatic and geologic data that are used to predict river segment carbonate chemistry using a machine learning framework.
- A greenhouse gas emissions trajectory over a thousand-year time interval.

Processes

The model accounts for:

- Dynamic re-equilibration of the carbonic acid system in river/stream waters and surface oceans.
- Formation of clay and carbonate mineral phases (and associated CO_2 re-release) during transport.
- Mixing of different water masses (both in the river network and in the oceans).

Outputs

The model outputs are estimates of the extent of carbon removed during enhanced weathering that remain stored as bicarbonate in either rivers or the oceans over a specified time frame, from decades to hundreds of thousands of years.

Baseline

By comparing a baseline model run—with the same assumptions and forcings—to a run with a basalt amendment, the Lithos model pipeline allows for a comprehensive, robust "cradle-to-grave" assessment of carbon capture permanence out to thousand-year timescales.

Additional models and simulation approaches

- An eco-hydrological and biogeochemical model by Cipolla *et al.* [52, 53], which is relatively less complex than SCEPTER, and considers soil physics and hydrology parameters, organic matter decomposition, ionic concentration changes, and plant dynamics. Validation of this model under field conditions is still work in progress.
- A variation of the Shrinking Core Model was used by Vink and Knops to evaluate the environmental risk assessment of nickel release by ERW from olivine weathering materials [61]. This publication does not include real-life validation examples, but in November 2022, Vink, Giesen, and Ahlrichs had authored a technical report where results of several mesocosm olivine experiments include monitoring of ERW rates and nickel concentrations in soil pore water over two years [62].
- A global model of carbon capture efficiency from alkalinization efforts such as ERW by Bertagni and Porporato [63]. This model provides a quantification of the alkalinization carbon-capture efficiency (ACE) as a function of water chemistry. It can not be currently with field data because it would require global ERW applications and monitoring at scale.

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