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earth

Puro Standard

**Enhanced Rock
Weathering
Methodology**

Edition 2022

Enhanced Rock Weathering in Soil Methodology

↑ **Note to reader**

Reasons for starting with a methodology protocol now

Enhanced Rock Weathering (ERW) processes have been considered for almost 30 years to remove atmospheric carbon dioxide (Lackner et al., 1995; Seifritz, 1990). However, ERW is **not included** in any existing carbon crediting programs. Doing so will put ERW under the control of standards which seek to enhance the safety and profile of such CO₂ removal activities. Addressing scientific uncertainties through field trials and collecting in field data will be paramount in moving from theoretical approximations of weathering to measured results. Evaluating practical issues relating to measurement, reporting and verification (MRV), including what to measure and the associated cost, as well as engaging with industry and government are crucial to advancing ERW as a commercial carbon removal technology.

Quantification of how much carbon is removed through ERW at a point in time is challenging. This is due to a small change in the measurable weathering result (signal) relative to the underlying background result and the slow nature of the process in soil under natural environmental conditions. Quantification is further complicated as part of the stored carbon (bicarbonate and major ions) is in the aqueous phase and transported from the site of application by local hydrology. A general scientific consensus on best practice of simulation methods and associated MRV does not yet exist.

Multiple other aspects of ERW activities have to be defined and adhere to standards. For this methodology the working group has done their best to define safeguards and quantification approaches aligned with the latest science. This methodology ensures little to no environmental impact, which is critical to increasing public acceptance of ERW. With these safeguards in place, we collectively believe ERW field trials can be designed and implemented safely. Field work and associated experiments will in time improve this methodology as well as collective understanding of this domain.

Why now?

Enhanced Rock Weathering on land has significant CO₂ removal **potential** at a global scale. There is a lot we already know about ERW and a lot that we don't know. Operational ERW projects are needed to fill the knowledge gaps. Commencing ERW projects under the control of this methodology will enhance safety and deliver knowledge needed to make ERW a sound and reliable carbon removal activity, with many co-benefits.



Thank You

The **Puro team** would also like to extend an **enormous thank you** to all of those involved in this process of developing this methodology. It has been a team effort from day one and this work cannot be done by one group or one company. I have been hugely appreciative of the way given the **diverse** skill sets and backgrounds we have all collaborated, learnt from one another and produced a methodology for this approach. It has been a real pleasure working with you all.

Additionally an enormous thank you to our **Advisory Board** for providing constant feedback and input throughout.

Good luck to all of you starting to do real work in this space and making theory a reality, safely.

November, Helsinki

The Working Group

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Remark

This methodology provides general **information** on enhanced rock weathering as well as actual **requirements** which must be met by all projects seeking certification by the Puro Standard. Across the entire methodology, the **requirements** correspond to **numbered paragraphs**, e.g. “4.4.2. *The CO₂ Removal Supplier shall provide evidence regarding the right or authorisation to spread the rock onto the application site.*”

Glossary

‡ The glossary provides the definitions of certain important terms as they are used in this document. For additional definitions, please see the Puro Standard General Rules.¹

Application site - a single plot of land or a group of plots where the *weathering material* is being spread.

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 carbonates*.

CO₂ 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 an *application site*.

Enhanced Rock Weathering - a CO₂ 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*.

IC-VCM - Integrity Council for the Voluntary Carbon Market.

Model - a set of equations implemented in computer software that is utilized to make a prediction related to the weathering reactions and the associated carbon dioxide removal depending on a certain number of input parameters. The word 'model' includes the analysis and interpretation of the predictions produced by the software.

Production facility - a facility capable of CO₂ removal according to the present methodology. For enhanced rock weathering, the production facility coincides with the *application site*.

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

¹ <https://connect.puro.earth/puro.earth.marketplace.rules>

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

Weathering material - the material being spread to the *application site*, 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 total alkalinity or total inorganic carbon) indicative of weathering reactions taking place in the soil and utilized in the quantification of CO_2 sequestered. Reliable sequestration quantification methods often rely on several different weathering signals.

1. Introduction and CO₂ removal method overview

1.1. Process Overview

‡ The introduction provides an overview of how enhanced rock weathering (ERW) in soil captures CO₂, how the CO₂ is stabilized and stored, as well as the potential positive and negative aspects of this carbon removal method.

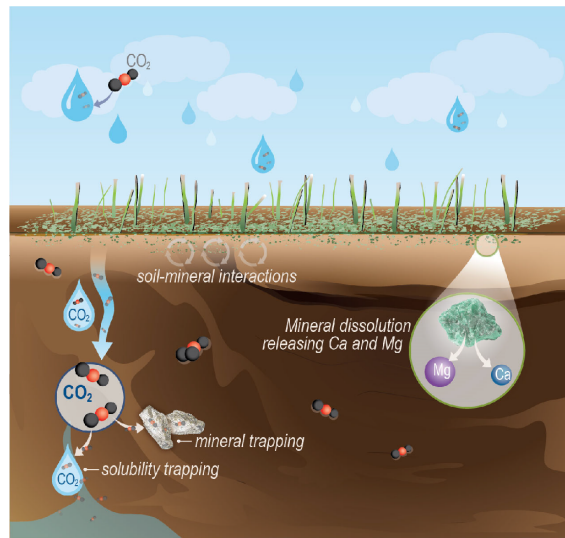


Figure 1. Enhanced Rock Weathering - Sandalow, D., et al. (2021)

Natural Weathering

In nature, rocks and minerals naturally bind carbon dioxide from the atmosphere in a process known as **weathering**. 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 the minerals contained in them. The end result of this chemical reaction is that the minerals slowly dissolve over long periods of time and in the process, the carbon dioxide that was dissolved in the water is transformed into other molecules, thus preventing its release back into the atmosphere.

Natural weathering happens at the Earth's surface, removing about 1.1 Gt CO₂ per year (Strefler et al., 2018) but at extremely slow rates over geological time scales. **Accelerating** Earth's natural weathering processes to sequester atmospheric carbon dioxide has been considered for almost 30 years (Lackner et al., 1995; Seifritz, 1990). **Enhanced Rock Weathering (ERW)** accelerates these natural processes of weathering.

ERW can be carried out in terrestrial (soils), coastal and aquatic environments. This methodology only considers the application of weathering material in **terrestrial** (land-based) environments, more specifically, **in soil**.²

Enhanced Rock Weathering

In enhanced rock weathering (**ERW**), this natural phenomenon is sped up by spreading crushed rock or other material (e.g. the surplus from a quarry operation or non-toxic industrial waste such as concrete) onto the ground, where the increased surface area of the material speeds up the dissolving process (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 your mouth than the fine strands of cotton candy).

The process can then be further enhanced by selecting the optimal type of weathering material, soil types, climate regions, etc., resulting in a viable method of permanent **carbon dioxide removal** from the atmosphere. In summary, ERW is a way of **geochemically sequestering** carbon dioxide (CO₂) utilizing natural chemical reactions, with the aim of permanently removing CO₂ from the atmosphere.

More precisely, in ERW, materials containing **silicate minerals** that contain cations (positively charged ions) are exposed to CO₂ and in the presence of water results in an acid-base neutralization reaction. The reaction leads to the formation of **dissolved carbonates** (i.e. CO₂ as gas, as bicarbonate HCO₃⁻ and carbonate CO₃²⁻ in water) and/or **solid carbonates** (i.e. CO₂ is stored in carbonate minerals such as CaCO₃).

The **primary goal** of ERW techniques is therefore to **accelerate** and **optimize** weathering reactions by:

- Selecting the most **reactive** types of material.
- Increasing the **surface area** of the material.
- Applying the material to **optimal soils** and **climatic conditions**.

² In the **Puro Standard**, weathering in industrial (controlled) conditions for the production of a usable carbonated material is covered by the methodology **Carbonated Building Material**. Enhanced weathering in coastal areas and ocean alkalization are *not yet* covered under the Puro Standard.

1.2. Pros & Cons

Positive (+) aspects of ERW

As a method for CO₂ removal and sequestration, **ERW** has several strengths:

- **First**, mineral resources (rock types and application surfaces) are abundant and available in many countries around the globe.
- **Second**, rock mining, grinding and spreading are very well established technologies.
- **Third**, enhanced weathering is among the most permanent form of carbon removal, with little risks of natural or anthropogenic reversibility.
- **Fourth**, ERW can be associated with positive co-benefits in agriculture and surrounding water catchment e.g. the release of nutrients (potassium, phosphorus, and some micronutrients), enhancing agronomic productivity and reducing fertilizer use, water retention, change in hydrological soil properties and affect soil pH, or acidification mitigation in aquatic ecosystem (through increase in alkalinity) (Swoboda et al., 2022).
- **Fifth**, the residual waste material from other processes (such as cement kiln dust or demolished and returned concrete) can be beneficially used for ERW approaches to carbon removal.

Negative (-) aspects of ERW

There are also several **challenges** and **risks** associated with ERW as a CO₂ removal and sequestration method:

- **First**, ERW in soils does not happen instantaneously after application, but rather spans over **multiple years** and even decades.
- **Second**, 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).
- **Third**, some rock or mineral types release **toxic heavy metals** as part of the dissolution reaction, for example nickel and chromium. This often limits application rates, as part of strategies to mitigate severe negative effects on ecosystem and human health.
- **Fourth**, rock grinding to **very fine particle sizes** can lead to emission of respirable particles potentially affecting human health.

- **Fifth**, both **monitoring and modeling** of weathering in field conditions is challenging, owing to the dynamic nature and the variability of natural ecosystems and the slow reaction rate.

Overall, these negative aspects reflect the fact that ERW in soils is still considered to have a “low technology readiness level”, with “medium” scientific evidence and “low” scientific agreement, relative to other removal methods (IPCC, SR1.5, Chapter 4; IPCC, AR6, WGIII, Chapter 12.3). To date, ERW has only been demonstrated in laboratory experiments and models that do exist have only been partially validated using soil pot trial experimental data (Kelland et al., 2020; Vienne et al., 2022). Further model validation is in progress as new data become available.

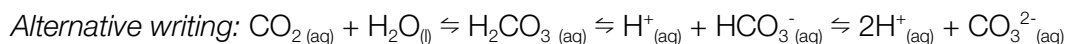
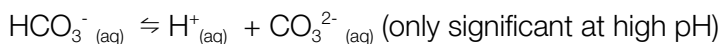
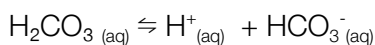
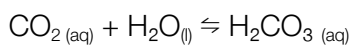
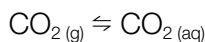
The most suitable weathering material usually contains minerals with high amounts of magnesium and calcium. The suitability of natural rocks for enhanced weathering comes from a combination of factors, including **volume** of rock available, **mineral composition**, and levels of **potentially toxic 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.

1.3. Reaction chemistry & sequestration

Enhanced weathering can be represented by two (2) or three (3) **main reactions**:

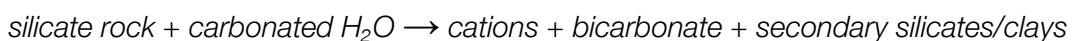
(i) CO₂ dissolution (*gas in a liquid*), **(ii)** mineral dissolution (*solid in a liquid*), and **(iii)** carbonate precipitation (attaching Ca to carbonate). While the two first reactions are fundamental to rock weathering, the carbonate precipitation process **(iii)** only occurs in specific situations. These reactions are presented below:

i) CO₂ dissolution in water:

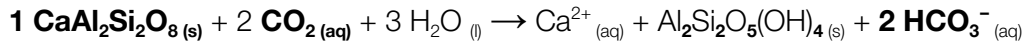


ii) Mineral dissolution:

The actual reaction chemistry here depends on the mineral considered. It however follows the generic pattern below:



For example, the dissolution of 1 mol of **anorthite** (the mineral) in the presence of CO₂ results in the formation of **2 mol** of bicarbonate, and secondary silicates:



Note that **1 mol** of alkali earth metal leads to **2 mol** of CO₂ stored, if fully performed.

In the above example the reactions **(i)** + **(ii)** are occurring in **parallel** and this is what is being defined more broadly as weathering.

iii) Calcium carbonate precipitation (formation of calcium carbonates):

An additional reaction which may happen in specific cases (for example high pH soil, or low moisture soil) is carbonate precipitation in the soil.



This results in **1 mol** of CO₂ **going back to the atmosphere**. Therefore, **1 mol** of alkaline earth metal leads to **1 mol** of CO₂ stored.

In summary, there are two pathways leading to CO₂ removal through weathering in soil:

- **Pathway 1:** reactions **(i)** and **(ii)**, leading to 2 mol of CO₂ stored, in the form of bicarbonate, per mol of alkali earth metal.
- **Pathway 2:** reactions **(i)**, **(ii)** and **(iii)**, leading to 1 mol of CO₂ stored, in the form of carbonate, per mol of alkali earth metal

It is important to note that the reaction of mineral dissolution by carbon dioxide is in competition with mineral dissolution by other stronger acids that may be present in the soil. In addition, bicarbonates formed through the first pathway move in the water catchment and up to oceans. Along the way, a fraction of the formed bicarbonates can form carbonates.

Ultimate fate of dissolved carbon

As the weathering material **dissolves to release cations**, other elements contained in the material must also be dissolved (silicates, other metals), affecting the duration of the overall reaction. These other dissolution reactions are not presented here.

In soils, the above reactions happen in parallel, 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, so called indirect weathering). Therefore, ERW in soils leads to the formation of both **carbonates** and **bicarbonates**, in variable proportions determined by the local environmental conditions.

- The **bicarbonates** are dissolved in the soil water, and can therefore leach from the soil. Ultimately, bicarbonates flow with the groundwater, and can reach river streams and oceans, where CO₂ remains stably sequestered as bicarbonates in water, or precipitates in the ocean as solid carbonate minerals. In general this counteracts in a positive sense the acidity of these aquatic ecosystems.
- The solid **carbonate** minerals form part of the soil, and CO₂ remains stably sequestered in soils, as long as the local soil pH does not become acidic (in which case carbonates would potentially dissolve and bicarbonate would be re-formed), which is context-dependent.

1.4. Factors affecting the weathering rate

Whenever a mineral/rock is in contact with water it will tend to dissolve. The rate at which this dissolution reaction occurs is limited by many physical, chemical and even biological parameters. Dissolution is mainly driven by undersaturation.

The weathering reactions are limited by the dissolution of silicates in water, or in other words, silicate dissolution is rate-limiting. The mineral dissolution reaction freeing cations **(ii)** is slower than the dissolution of CO₂ in water **(i)** and the carbonate-forming precipitation **(iii)**.

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 cases where soils have been impacted by acid rain (sulphur oxide emissions producing sulphuric acid).

The rate of mineral dissolution in aqueous phase is proportional to the specific **surface area** of the material. Therefore, the process of rock crushing and milling improves the rate of enhanced weathering by increasing the size of the available surface to react.

The chemical 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, exhibit higher solubility in lower temperatures). Therefore, warm tropical regions (also known for their highly weathered and acidic soils) are often optimal areas for faster ERW in soils. The **aqueous phase composition** also affects kinetics: in particular, lower pH typically accelerates silicate dissolution (but disables carbonate precipitation), with different relationships and threshold levels for different minerals. Finally, the **weathering material composition** itself and its **surface passivation** affect the kinetics of dissolution.

The **timing** of carbon removal via ERW in soils spans over **years 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.

In soils, which are natural systems, the timing of carbon removal and the **complexity of measuring** is much more difficult to monitor and measure than engineered systems. This has implications for the ability to measure and to **reliably quantify** the carbon removal impact of ERW.

Many **biotic (living)** conditions 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 (Taylor et al., 2009; Thorley et al., 2015; Verbruggen et al., 2021), the secretion of acids, or stimulation of acid-generating nitrification by nitrogen-fixing plants (Bolan et al., 1991; Epihov et al., 2017; Perakis and Pett-Ridge, 2019). The knowledge of the inter-play between fungi and weathering rates will be an important dimension to more fully understand as understanding of this domain improves with time. **Invertebrates** in soil also contribute to weathering. Chemically, through the action of gut microbiota, and mechanically, by biopedturbation (van Groenigen et al., 2019; Vicca et al., 2022).

The **ideal conditions** for weathering are most often:

- *Low pH*
- *High water availability*
- *High temperature*
- *High CO₂ partial pressure*
- *Increased reactive surface area*

However, there are **outlier conditions** such as high physical erosion (freeze-thaw) in the arctic and the presence of organic acids can counteract weathering kinetics.

2. General principles of verifiable CO₂ Removals in Puro Standard

‡ This chapter outlines basic principles for all methodologies in Puro Standard, as well as alignment with the Integrity Council for the Voluntary Carbon Market (IC-VCM) core carbon principles.

2.1. Basic Principles

The methodology is the protocol that sets the requirements for **verification** and **quantification** of **CO₂ removal projects**. The development of methodologies into the **Puro Standard** is done in an open manner with an expert working group, public consultation and review by an **Advisory Board**. The guiding principles are:

1. Transparency

Transparency by all parties fosters trust and reduces transaction costs in the operation of markets. This helps markets operate effectively and deliver desirable outcomes. Transparency is critical to building a high level of assurance for the buyers and sellers of CORCs (certified carbon removal). The public registry and the verification process is at its base an exercise in delivering transparency and confidence to market participants.

2. Application of evidence

Application of evidence and wherever possible **direct measurements** of carbon removed throughout the duration of the project is preferred in methodologies rather than relying only on estimates from simulated processes. The use and incorporation of **robust evidence** and field measurements in the design and operation of methodologies is good practice and particularly important in developing accuracy.

3. Monitoring, Reporting & Verification (MRV)

Monitoring, reporting, and verification (MRV) requirements are set in each methodology outlining the annual monitoring and record keeping of the project for the purposes of performance (CO₂ removal output) reporting. Each project reports the **performance** (CO₂ removal volumes), and submits it annually for **third-party verification**.

4. Refinement over time

This methodology and the measured performance of **ERW** projects will be **refined and improved over time** and shall be based upon the **best available science**. As more data from field trials becomes available the scientific knowledge base of this removal category will be improved. Indeed, this principle of calibration based on new field data is central to any quantification method going forward. Over time, the ERW projects will collectively develop large data sets that will allow for the refinement and validation of quantification

approaches to calculate the removed volumes, along with many other of the core aspects of this methodology.

2.2. Alignment with Core Carbon Principles³

The Integrity Council for the Voluntary Carbon Market (**IC-VCM**), is an independent governance body for the voluntary carbon market. Their target is to build integrity, so that high-quality carbon credits efficiently mobilize finance towards urgent mitigation and climate resilient activities. The **Puro Standard** is following the **Core Carbon Principles (CCPs)** issued by the IC-VCM.

Principles for carbon-crediting programs

1. Mitigation activity information (CCP 02)

The carbon-crediting **program** shall provide comprehensive and transparent information on all credited mitigation activities. The information shall be publicly available in electronic format, and scrutiny of mitigation activities shall be accessible to non-specialised audiences.

2. Program governance (CCP 05)

The carbon-crediting **program** shall have effective program governance to ensure transparency, accountability and the overall quality of carbon credits.

3. Registry (CCP 06)

The carbon-crediting **program** shall operate or make use of a registry to uniquely identify, record, and track mitigation activities and carbon credits issued to ensure credits can be identified securely and unambiguously.

4. Robust independent 3rd party validation & verification (CCP 07)

The carbon-crediting **program** shall have program-level requirements for robust independent third-party validation and verification of mitigation activities.

5. Sustainable development impact and safeguards (CCP 09)

The carbon-crediting **program** shall have clear guidance, tools, and compliance procedures to ensure mitigation activities conform with, or go beyond, widely established best industry practices on social and environmental safeguards, while delivering net positive sustainable development effects.

³ The integrity Council for the Voluntary Carbon Market - Part 2 - Core Carbon Principles
<https://icvcm.org/wp-content/uploads/2022/07/ICVCM-Public-Consultation-FINAL-Part-2.pdf>

Principles for Projects (mitigation activities)

6. Permanence (CCP 04)

The GHG emission reductions or removals from the **mitigation activity** shall be permanent, or if they have a risk of reversal, any reversals shall be fully compensated.

7. Robust quantification of emissions reductions & removals (CCP 08)

The GHG emission reductions or removals from the **mitigation activity** shall be robustly quantified, based on conservative approaches, completeness and sound scientific methods.

8. Additionality (CCP 01)

The greenhouse gas (GHG) emission reductions or removals from the **mitigation activity** shall be additional, i.e., they would not have occurred in the absence of the incentive created by carbon credit revenues.

9. No double counting (CCP 03)

The GHG emission reductions or removals from the **mitigation activity** shall not be double-counted, i.e., they shall only be counted once towards achieving mitigation targets or goals. Double counting covers double issuance, double claiming, and double use.

10. Transition towards net-zero emissions (CCP 10)

The **mitigation activity** shall avoid locking in levels of emissions, technologies or carbon intensive practices that are incompatible with achieving net zero emissions by mid-century.

3. Point of creation of the CO₂ Removal Certificate (CORC)

‡ This chapter defines the role of the CO₂ removal supplier and the Point of creation of the credit, where and when the carbon dioxide removal certificates (CORCs) are created.

3.1. CO₂ Removal Supplier

The CO₂ Removal Supplier is the authorized party to represent the end-to-end supply chain of enhanced rock weathering (ERW) activity. The CO₂ 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.

3.2. Point of creation

The **CO₂ 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.⁴

- 3.2.1. The amount of CORCs issued at a given time shall be based on the actual amount of CO₂ sequestration that has *already happened* so far, as verified by the **in-field measurements** performed by the CO₂ Removal Supplier. This is required to ensure the credibility of the ERW methodology, given the current uncertainties associated with ERW simulations.
- 3.2.2. Initial CORCs can be issued at **any point in time** after the application of the weathering material provided that the CO₂ Removal Supplier is able to produce **evidence** in the form of in-field measurements quantifying the amount of CO₂ already sequestered.⁵
- 3.2.3. **Continued** in-field measurements are required from the CO₂ Removal Supplier throughout the lifetime of the project in order to quantify the amount of CO₂ sequestered (*Section 7.3*).

⁴ 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 e.g. issuing pre-CORCs (for which no removal claims can be made) based on simulated or expected results; with the project's own equity; or via various other means of funding.

⁵ Although no definite timeline is specified for the measurements, a reliable detection of a weathering signal will likely not occur in days or weeks. Weathering is a slow process and there is currently no scientific consensus on which measured signals provide the most reliable quantification of the carbon sequestration associated with ERW.

- 3.2.4. The amount of carbon dioxide sequestered must also be **simulated** initially (pre-application) using application site-specific soil and climate conditions. The simulations shall be updated alongside on-site monitoring and measurement of the weathering reactions e.g. via increased alkalinity or other approaches (*Section 7.3*).

4. Eligibility requirements and verification

↓ *This chapter defines what are **eligible activities** for enhanced weathering and lists the associated **requirements**, as well as **proof and evidence for verification**. The terminology used relates to Puro Standard General Rules⁶ for carbon removal.*

4.1. General eligibility requirements

- 4.1.1. An **eligible activity** is an activity capable of storing carbon dioxide in the form of carbonate or bicarbonate ions or solid carbonate minerals via the application of a weathering material to an **application site**. An **application site** can represent a single plot of land or a group of plots.
- 4.1.2. The **application site** corresponds here to the **Production Facility** of CO₂ Removal Certificates, as per the terminology defined in the Puro Standard General Rules.
- 4.1.3. A **Production Facility** and the associated activity is determined as eligible for issuance of CO₂ removal certificates, once the Production Facility has undergone a process of **third-party verification** by a duly appointed auditor performing a **Production Facility Audit**. 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 CO₂ Removal Supplier. These are included throughout the methodology as numbered requirements, e.g. 4.1.1.
- 4.1.4. The Production Facility Auditor collects and checks the standing data of the CO₂ 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 CO₂ Removal Supplier's organization legitimately exists.
 - The CO₂ 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.

⁶ <https://connect.puro.earth/puro.earth.marketplace.rules>

4.2. Requirements for additionality

- 4.2.1. The CO₂ Removal Supplier shall be able to demonstrate **additionality**⁷, meaning that the project must convincingly demonstrate that the CO₂ 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.
- 4.2.2. To demonstrate additionality, the CO₂ Removal Supplier must show that the project is **not required by existing laws**, regulations, or other binding obligations.
- 4.2.3. To demonstrate additionality, the CO₂ Removal Supplier must provide full project financials and **counter-factual** analysis based on baselines that shall be project-specific, conservative and periodically updated.

4.3. Requirements for prevention of double-counting

- 4.3.1. The CO₂ Removal Supplier shall ensure that the CO₂ 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.
- 4.3.2. To demonstrate no double-counting, the CO₂ 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.
- 4.3.3. To demonstrate no double-counting, the CO₂ 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.
- 4.3.4. 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 CO₂ Removal Supplier.

4.4. Requirements for environmental safeguards

- 4.4.1. The CO₂ Removal Supplier must demonstrate **safe weathering material sourcing**: origin of the raw materials, the raw material is sourced sustainably in accordance with local regulations, in particular, mining regulation. Any exploitation permit, land use right, environmental permits, as well as certification of operations, shall be part of the proof.

⁷ Removals are **additional** if they would not have occurred without carbon finance. Developers 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").

- 4.4.2. The CO₂ Removal Supplier shall provide evidence regarding the **right or authorisation** to spread the weathering material onto the application site.
- 4.4.3. The CO₂ 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.
- 4.4.4. The CO₂ Removal Supplier must 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 (*Section 5.2*).
- 4.4.5. The CO₂ 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 and the soil samples, determining concentrations of potentially **toxic elements** with appropriate methods (*Section 5.3*).
- 4.4.6. 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.
- 4.4.7. Where there is **no local regulation** guiding the acceptability of levels of potentially toxic elements, **EU thresholds will be used as the threshold limits** (*Section 5.3*).
- 4.4.8. When there is a **local regulation** setting contaminant thresholds that differ to those set by the EU⁸, 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 (*Section 5.2*).
- 4.4.9. The CO₂ Removal Supplier must prepare a **monitoring plan** detailing any associated resources, for the time of the monitoring phase (post-application).

4.5. Requirements for social safeguards

- 4.5.1. The CO₂ Removal Supplier shall be able to demonstrate the **impact on communities** by the ERW activity. Where applicable, 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 shall be provided.
- 4.5.2. To demonstrate **local stakeholder consultation**, the CO₂ 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 CO₂ Removal Supplier shall be able to demonstrate with documents the policy and procedures in place to address potential grievances.

⁸ 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. <https://data.europa.eu/eli/reg/2019/1009/oj>

- 4.5.3. As part of stakeholder consultation, the CO₂ Removal Supplier shall communicate the potential **health risks** and limits concerning toxic contaminants in the applied weathering material (*Chapter 5*).
- 4.5.4. The CO₂ Removal Supplier is 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).

4.6. Requirements for robust quantification of carbon removal and net-negativity

- 4.6.1. The CO₂ Removal Supplier must provide a **life cycle assessment (LCA)** quantifying the greenhouse gas emissions related to the ERW activity, as per the scope and system boundaries defined in *Chapter 6*, and following the general LCA guidelines described in ISO 14040/44.
- 4.6.2. The CO₂ Removal Supplier must provide a written description of the **simulation approach** used to quantify the weathering process and the expected carbon removal, as per the requirements defined in (*Section 7.3*).
- 4.6.3. The CO₂ Removal Supplier must 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.
- 4.6.4. Based on the LCA results and the initial simulation results, the CO₂ 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.
- 4.6.5. The CO₂ Removal Supplier shall conduct a **geochemical assay** detailing the composition of the weathering material before its application on site.
- 4.6.6. The CO₂ Removal Supplier shall conduct a **soil analysis** at the application site before the spreading of the weathering material. The analysis shall consist of the application site-specific soil properties (such as pH, moisture content, etc.) that are required to establish the **baseline situation** in the weathering model utilized by the CO₂ Removal Supplier (*Requirement 3.2.4* and *Section 7.3*).
- 4.6.7. The CO₂ Removal Supplier shall provide evidence, in the form of **laboratory results** and/or **in-field measurements**, that supports the project-specificity of the simulations performed. 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** needed to perform the simulations (e.g. rock or mineral elemental and mineralogical composition, particle size, surface area, soil pH, soil texture).

- 4.6.8. For issuance of CORCs, the CO₂ Removal Supplier must perform, at least annually after application, **in-field measurements** to **validate** the simulated carbon removal and update the simulations if necessary, as per the requirements defined in *Section 7.3* and per the rules for CORC creation defined in *Chapter 3*.
- 4.6.9. The CO₂ Removal Supplier must be capable of **metering, quantifying, and keeping records** of the parameters needed to quantify the CO₂ 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.
- 4.6.10. The CO₂ Removal Supplier must ensure that any **instruments** used for data collection are in place and adequately calibrated at all times. The data records are kept in a **reliable data system**.

5. Environmental & Social Safeguards

↓ *This chapter outlines the environmental and social safeguards that need to be met, as well as risk management measures that are put in place to adhere to the overarching principle of do no harm. The chapter also sheds light on the major environmental risks associated with ERW and evaluation approaches of these risks.*

5.1. General principles and requirements

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. 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

Thereby, **projects must**:

- 5.1.1. Demonstrate and evidence **engagement with local communities** in an ongoing and transparent manner throughout the project lifetime.
- 5.1.2. Not operate on land that has been identified as **culturally sensitive** or cause community displacement.
- 5.1.3. 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).
- 5.1.4. Demonstrate and evidence that projects have a **low risk** of any materially **negative impacts** on the surrounding **local communities**.
- 5.1.5. 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 (Swoboda et al., 2022; Manning and Theodoro, 2020).
- 5.1.6. Inform, during **public stakeholders consultations**, the local community of the acceptability **limits for contaminants** followed in these projects.

In addition, 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.

⁹ Microsoft criteria for high-quality carbon dioxide removal.
[Criteria for high-quality carbon dioxide removal](#)

Thereby, as part of the Puro eligibility process, **projects must**:

- 5.1.7. Perform an environmental risk assessment (**ERA**) as prescribed in (Section 5.2).
- 5.1.8. For information, current knowledge on the environmental risks associated with PTEs or contaminants present in weathering materials is summarized in (Section 5.3).

5.2. Environmental risk assessment and management

- 5.2.1. The CO₂ 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 CO₂ 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.
- 5.2.2. The CO₂ 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.
- 5.2.3. The CO₂ 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.
- 5.2.4. The **ERA** shall be **completed before** the decision was taken to apply weathering material at the potential application site.
- 5.2.5. The 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 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) could be considered to combine restoration of the land and CO₂ removal.
 - Proper analysis of **food safety**: the effects of crushed material applications on the quality and yield of crops from published studies.
- 5.2.6. The risk assessment shall be **conservative** in its assumptions and calculations.
- 5.2.7. The risk assessment shall be **reviewed by an independent third-party**, with relevant expertise.

5.2.8. The risk assessment performed by the CO₂ Removal Supplier shall follow the guidance from the **US EPA**¹⁰, **the EU EFSA**¹¹, or other locally relevant institutions. The environmental risk assessment shall follow the outline below:

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

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 the specified application site (e.g. agricultural soil, forest soil, urban soil) may introduce heavy metals, radionuclides or 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.

- **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 site (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 site. This depends both on the **weathering material** selected, and the **local conditions** at the application site.

- **Step 2.2 Exposure characterisation**

This step defines what are the **exposure pathways** through which the elements of concern (metals, asbestiform minerals or radionuclides) can reach humans, fauna and flora, or 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

¹⁰ <https://www.epa.gov/risk/about-risk-assessment>

¹¹ <https://www.efsa.europa.eu/en/topics/topic/environmental-risk-assessment>

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 measure**

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: i) cultivation of food crops that do not uptake specific metals of concerns, ii) cultivation of energy crops that actually uptake the metals of concerns, for subsequent incineration and storage of ashes, iii) other phytoremediation methods, iv) 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 i) not permitted due to non-manageable risk, ii) permitted, with no major risks, or iii) permitted provided that adequate mitigation measures are implemented.

5.3. [Guidance on risk evaluation of potentially toxic elements in weathering material](#)

During the weathering reactions, elements are released into soil. Depending on the material composition, elements released can also include **potentially toxic elements** which above certain levels may have detrimental effects, such as heavy metals (e.g., nickel, chromium VI, cadmium, uranium), radionuclides (e.g. ^{40}K , ^{226}Ra , or ^{232}Th), or 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. 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.

Heavy metals

The levels and effects of heavy metals in agricultural and forest soils have been studied for decades. In parts of the world, estimates of heavy metal concentrations in soils are

available (e.g. Toth et al. 2016), and several guidelines or laws exist to regulate the addition of heavy metals to soil.

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

- **Maximum metal concentrations** in the **applied material** (e.g. expressed in kg of metal per kg of fertilizer), e.g. the EU has compulsory regulation for fertilizers.¹²
- **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 kg metal per kg soil), e.g. the European Joint Research Center has compared thresholds defined in various Member State countries (Carlon 2007).
- **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.¹³ 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.¹⁴
- 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 with 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 occurring 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, namely mobility

¹² 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. <https://data.europa.eu/eli/reg/2019/1009/oj>

¹³ Council Directive of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture (86/278/EEC). <https://data.europa.eu/eli/dir/1986/278/2022-01-01>

¹⁴ Guidance on Sewage sludge in agriculture: code of practice for England, Wales and Northern Ireland (2018) UK Environment Agency. <https://www.gov.uk/government/publications/sewage-sludge-in-agriculture-code-of-practice/sewage-sludge-in-agriculture-code-of-practice-for-england-wales-and-northern-ireland>

through the soil columns, plant uptake, and losses to water, as well as exposure pathways to humans.

- 5.3.1. At the moment, ERW projects must consider, quantify and discuss heavy metal related risks in the **Environmental Risk Assessment (ERA)** submitted to Puro. 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.

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, organa-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 certain level of risk (*Table 1*). Re-using these threshold values in the context of ERW might indicate a safe ERW activity if the ERW activity has similar or smaller 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 1*, but may still be deemed safe to use according to soil maximum concentrations or other context-specific factors.

Table 1. Limit values for heavy metal contents in inorganic soil improver, reproduced from Annex I, PFC 3(B), in the EU regulation for fertilizing products¹⁵

Metal	Limit (mg/kg dry matter)
(a) cadmium (Cd)	1.5
(b) hexavalent chromium (Cr VI)	2.0
(c) mercury (Hg)	1.0
(d) nickel (Ni)	100
(e) lead (Pb)	120
(f) inorganic arsenic (As)	40
(g) copper (Cu)	300
(h) zinc (Zn)	800

¹⁵ 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. <https://data.europa.eu/eli/reg/2019/1009/oj>

- **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 Carlon (2007), while other international guidelines were compiled in Monchanin et al. (2021, Table S2). An example of such guideline values is presented in *Table 2*, and is taken from the Finnish governmental decree on the Assessment of Soil Contamination and Remediation Needs (2007)¹⁶. Values from this decree are presented here as relevant for agricultural soils, because of precedents in academic literature (Toth et al. 2016) and international UN reports (UNEP 2013)¹⁷.

Table 2. Limit values for metal contents in soils derived from the Finish governmental decree on the Assessment of Soil Contamination and Remediation Needs (2007).

Metal	Limit (mg/kg dry matter)
Cadmium (Cd)	1.0
Chromium (Cr)	100
Mercury (Hg)	0.50
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

¹⁶ Ministry of the Environment, Finland (2007). Government Decree on the Assessment of Soil Contamination and Remediation Needs.

<https://www.finlex.fi/sv/laki/kaannokset/2007/en20070214.pdf>

¹⁷ UNEP (2013) Environmental Risks and Challenges of Anthropogenic Metals Flows and Cycles, A Report of the Working Group on the Global Metal Flows to the International Resource Panel. van der Voet, E.; Salminen, R.; Eckelman, M.; Mudd, G.; Norgate, T.; Hirschier, R.

Asbestos

Asbestos and asbestiform minerals are a type of naturally occurring fibrous silicate material, which can cause serious human health effects via exposure through inhalation. 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. 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 HSG248¹⁸. 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 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.

- 5.3.2. At the moment, ERW projects must consider and discuss **asbestos** related risks and demonstrate that asbestiform minerals are not present above trace levels, in the **ERA** submitted to Puro.

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.

- 5.3.3. At the moment, ERW projects must consider and discuss **radionuclide** related risks in the **ERA** submitted to Puro.

¹⁸Asbestos: The analyst’s guide for sampling, analysis and clearance procedures (HSG248)
<https://www.hse.gov.uk/pubns/priced/hsg248.pdf>

6. Assessment of life cycle greenhouse gas emissions

‡ This chapter defines the type of life cycle assessment (LCA) required and the system boundaries of the activity. This includes process boundaries, spatial boundaries, and time boundaries. These emissions are then deducted from the captured and stored CO₂ to obtain the net CO₂ Removal CORCs.

6.1. LCA and process boundaries

- 6.1.1. For the purpose of CORC determination, the CO₂ 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 both a report and supporting calculations.
- 6.1.2. 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 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.
- 6.1.3. 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.

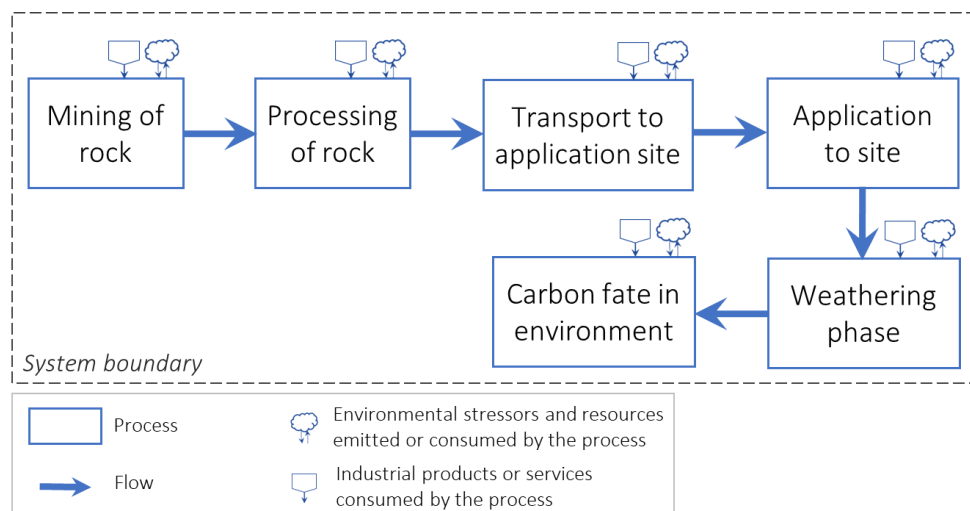


Figure 2. Generic process boundaries for ERW in soils.¹⁹

¹⁹ 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, “Weathering phase” and “Carbon fate in environment” take place simultaneously, although illustrated sequentially in the flowchart”.

6.1.4. 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:

- **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 (*Requirement 6.1.5*). 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 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 (*Requirement 6.1.7*).
- **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 today (Renforth and

Henderson, 2017), 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 modeling of carbon stored (*Chapter 7*).

- 6.1.5. In case the weathering material is a **waste or secondary product** of another process, it is recommended to apply a cut-off approach²⁰ 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 applied to the weathering material must be accounted for (e.g. storage, handling, transport).
- 6.1.6. 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.
- 6.1.7. Impact from **direct land use change (dLUC)** here 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 activity²¹.
- 6.1.8. 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 CO₂-eq and the contributions of CO₂-fossil, CH₄, N₂O, 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.

²⁰ Description of the cut-off system model is available on the website of the ecoinvent life cycle database: <https://ecoinvent.org/the-ecoinvent-database/system-models/#!/allocation-cut-off>

²¹ 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.

6.2. 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.

6.2.1. Spatial boundaries of 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 site: the area and the geolocation of the application site 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 (groundwater, watershed, rivers, ocean entry point, aquifer).

6.2.2. Time boundaries of LCA:

- 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 (derived from modeling) of the time needed for reaching various thresholds of weathering of the material must be given. 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).

6.3. 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 exists²². 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.

²² Microsoft Carbon Dioxide Removal RFP Guidance Document (2021) pp 5-6.

- 6.3.1. 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.

7. Calculation method for the quantification of CO₂ removal

↓ This chapter presents requirements and guidelines for the quantification of the CO₂ sequestered by the ERW activity or project and the method for calculating the amount of the associated carbon dioxide removal certificates (CORCs).

The overall equation for CORCs is presented in Section 7.1, and the subsequent Sections 7.2 and 7.3 summarize the requirements for the calculation of each term. Sections 7.4 and 7.5 provide suggestions and practical information for ERW modeling and the subsequent experimental model validation. Finally, two examples of different ERW models currently utilized are presented in Section 7.6.

7.1. Overall equation

$$CORCs = E_{stored} - E_{SupplyChain}$$

Description	Amount of net CO ₂ -eq removed by the applied weathering rock, after the selected time horizon	Amount of CO ₂ stored via weathering of the applied rock, at the application site, after the selected time horizon	Life cycle greenhouse gas emissions arising from mining of rock up to monitoring of the application site
Unit	tonnes CO ₂ -eq	tonnes CO ₂	tonnes CO ₂ -eq

Figure 3. Overall equation²³ to calculate the amount of CORCs generated by the ERW activity or project, over a selected time horizon.

The **overall equation** is made of two **(2) terms** (Figure 3) above:

- The first term (**E_{stored}**) describes the amount of carbon dioxide captured by the **weathering of the material applied**, including generation of *carbonate or bicarbonate ions* and *potential precipitation of solid carbonate minerals*, after a selected *weathering time* and stored for a given *time horizon*. Guidelines for quantification approaches of **E_{stored}** are given in Section 7.3.
- The second term (**E_{SupplyChain}**) represents the lifecycle greenhouse gas emissions arising from the mining activities, processing activities, transportation to deployment

²³ The tonnes unit refers here to **metric tonnes** (i.e. 1000 kg). All terms are counted as positive.

site, application to soil, monitoring, sampling and testing activities during the weathering phase. *Guidelines* for calculation of $E_{\text{SupplyChain}}$ are given in (Section 7.2).

7.2. Supply chain life cycle emissions ($E_{\text{SupplyChain}}$)

The term ($E_{\text{SupplyChain}}$) must be derived from a **life cycle assessment** (LCA of the ERW activity), according to the system boundaries defined in *Chapter 6* 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, i.e., including all life cycle stages (manufacturing, use, maintenance and disposal) of the processes involved. 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. 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 $E_{\text{SupplyChain}}$ can be adjusted for other application sites to reflect differences in, for example, transport distances.

7.3. Carbon capture, storage, and re-emission (E_{Stored})

The term (E_{stored}) describes the amount of carbon dioxide captured by the **weathering of the material applied to soil**, including generation of *carbonate or bicarbonate ions* and *potential precipitation of solid carbonate minerals*, after a selected *weathering time* and stored for a given *time horizon*.

- *Potential precipitation of carbonate minerals* may take place in soils, in surface waters, or in the ocean, with different relative importance depending on context and time horizon.
- *Weathering time* refers to the estimated time needed for reaching a given threshold of weathering that is included/assumed in the quantification of E_{stored} (e.g. 10 years after application, it is estimated that 70% of the material has weathered).
- *Time horizon* refers to the period over which carbon is guaranteed to be stored.

Requirements for simulation-based quantification approaches

Aspiring CORC suppliers shall submit their **quantification approach** for consideration by the Puro Standard, noting the **following requirements**:

- 7.3.1. **Project specificity:** the simulation shall capture site-specific project parameters, for instance the properties of the application site, rock mineralogy, specific surface area, the local climate such as rainfall, temperature and local hydrology.
- 7.3.2. **Dynamic simulation:** the simulation shall have an explicit time dimension showing the temporal changes of carbon storage at each year.
- 7.3.3. **Uncertainty estimation:** the simulation shall quantify or estimate the uncertainty on its outputs. Specifically, the **CO₂ 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.
- 7.3.4. **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 site, and a detailed monitoring plan must be made available, see *Section 4.6*.
- 7.3.5. **Simulation validation:** the simulation must be validated by site-specific empirical data or data that captures these specifics from a regionalised perspective. The CO₂ 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, *Section 4.6*).
- 7.3.6. **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.

7.3.7. **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.

Upon submission of an **E_{stored}** quantification approach by an aspiring CORC supplier, the Puro Standard and *selected experts* in the field shall critically analyze and test the submitted quantification approach. Then, a decision may be taken by the Puro Standard on the validity and acceptability of the quantification approach for CORC issuance, with the requirements listed above.

7.4. Guidelines for ERW models

Enhanced rock weathering is an inherently slow process, which often has a project duration of several years or decades. Therefore, modeling of the CDR (Carbon Dioxide Removal) potential and possible risks associated with ERW is needed in order to ensure efficiency and manage the risks involved in a given project.

Various **modeling approaches**²⁴ have been suggested in the literature, but to date (2022-11), 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.

In the following, it should be noted that 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.

1. 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 (not to deter innovation, but to prevent the use of old, discredited research). 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.

²⁴ For example: Moosdorf et al., 2014; Renforth et al., 2015; Taylor et al., 2017; Strefler et al., 2018; Goll et al., 2020; Beerling et al., 2020; Kelland et al., 2020; Lewis et al., 2021; Cipolla et al., 2021a; Cipolla et al., 2021b; Taylor et al., 2021; Cipolla et al., 2022; Vienne et al. 2022.

*Suggestions checklist:*²⁵

- Scientifically justifiable
- Based on published, peer reviewed research
- Commonly accepted theoretical background
- Mechanistic rather than fully empirical
- Data driven
- System dynamic approach (e.g. rock, soil, plant, atmosphere all interacting with one another)

2. 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 or 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)

3. Parameters

Different modeling approaches can vary significantly in the data required, but the model should at least include some thermodynamic data relating to the chemical reactions occurring during weathering, such as mineral solubilities, kinetic data relating to dissolution and precipitation of minerals, as well as thermodynamic and reaction kinetic constants.

Suggestions checklist:

- Weathering rates
- Thermodynamic data
 - Solubilities
 - Dissolution/precipitation kinetic data
 - Thermodynamic and kinetic constants

²⁵ The suggestions checklist provides a succinct summary of the points discussed within each section. Each point guides best practice for enhanced weathering models. These are separated according to the various aspects of modeling ERW.

4. 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. CO₂ dissolution and degassing, the dissolution and precipitation of mineral 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 infiltration 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 any 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 mineral oversaturation, 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
 - CO₂ dissolution / evolution
 - Mineral dissolution and precipitation
 - Acid-base and redox reactions
 - Sorption, ion exchange, and surface complexation
 - Gas dissolution and degassing
 - Respiration
- Transport of fluids and chemical species
 - Water infiltration
 - Advection, diffusion, dispersion
 - Ultimate fate of dissolved species
- Chemical kinetics (equilibrium constants, rate laws, etc.)

- Non-equilibrium kinetics
- Reversal of reactions
- Particle size effects
 - Grain size
 - Surface area
 - Mineral dissolution and precipitation
- Secondary effects
 - Clay and secondary mineral formation
 - Passivation of surface sites
- Spatial resolution
 - Depth profiles of concentrations and CO₂ partial pressure
 - Changes in pH or other conditions
- Changes due to environment
 - Uptake / release of ions / chemical species by plants
 - pH dependence of weathering rates or chemical reactions
 - Soil mixing (e.g. bioturbation by soil surface fauna, tilling)
- Changes through time
 - Application of material
 - Changes in physical or chemical parameters e.g. weathering material, porosity

5. Input

The inputs of the model should be at least partially project specific and tailored to the specific weathering material and environment that is used in the field. The model inputs should include the composition, both chemical and physical, of the weathering material being spread (e.g. stoichiometries, mass concentrations, surface area and particle size distributions of the material being spread) as well as data about the environment such as local climate conditions, water flow rates, 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
 - Stoichiometries
 - mass concentrations
 - Surface areas
 - Particle size distribution
- Environment data
 - Climate
 - Soil properties

- Water flow
- Amount of material spread

6. 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 CO₂ 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

7. 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. CO₂ release by respiration)

- Background weathering or other effects

8. 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 products such as pH, alkalinity or 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 some experimental EWR data

7.5. Guidelines for experimental validation

Assessing the realistic potential of enhanced weathering as a method for carbon dioxide removal is hindered by the fact that to date (2022-11), despite laboratory, mesocosm, and field trial studies, a comprehensive experimental body of data concerning weathering rates in field conditions is still missing. Even though the pool of available in-field experiments available for model validation is rather limited, the following examples could be considered for the past decade.²⁶

Various methods of **in-situ validation of weathering models** have been suggested in the literature, but as of yet (2022-11) the quantification of E_{stored} has not reached a scientific consensus, nor has it been included in IPCC's greenhouse gas inventory guidelines (last refined in 2019).

The following list of **weathering signals** 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 CO₂ sequestered**.

It is to be noted that the methodologies 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 CO₂ sequestration. The **validation approach** should also include controls (i.e. measurements on soil without ERW) since weathering signals are often relative.

In an effort to steer enhanced weathering validation forward, the present methodology does not favor any particular quantification approach, but instead underlines the requirement for a robust and accurate validation approach.

1. 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 CO₂ into dissolved inorganic carbon (e.g. HCO₃⁻). 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

²⁶ Renforth et al., 2015, Dietzen et al., 2018; Haque et al., 2019, Haque et al., 2020, Kelland et al., 2020, Pogge von Strandmann et al., 2021; Amann et al., 2020, Taylor et al., 2021; Khalidy et al., 2021; Amann and Hartmann, 2022; Vienne et al., 2022, Amann et al., 2022, Jariwala et al., 2022, Jorat et al., 2022.

dissolution is the driver for CO₂ 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 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 over several years, and specialized equipment to collect the water samples (e.g. lysimeters).

2. 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. For example, an alkaline environment favors precipitation of HCO₃⁻ into carbonates, which can increase weathering rates by removing weathering products from the soil solution.

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 pH, and the measurement of pH alone is not sufficient to quantify weathering or CDR.

3. Soil electrical conductivity

Description: Soil electrical conductivity refers to the ability of the soil to transmit or attenuate electrical current, and is a measure of soil water-soluble salt. It is mainly determined by the moisture content and ions dissolved in the soil pore water. Amann and Hartmann (2022) have outlined an approach to predict CO₂ sequestration using an empirical relationship between electrical conductivity and total alkalinity from lab column experiments and field observations.

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.

4. Concentration of major cations

Description: The concentration of major cations refers to the total concentrations of the primary positively charged ions (e.g. Mg^{2+} , Ca^{2+} , Na^+ , and K^+) dissolved into the soil pore water and/or sorbed to the soil. In ERW, the dissolving minerals release these cations into the soil where they contribute to the electrical conductivity. An increase in the concentrations of major cations in the soil is an indication that weathering is taking place.

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.

Cons: Similar compared to electrical conductivity measurements. Even though an increase in cation concentrations is an indicator of weathering, the method can not be used as a direct quantification of CO_2 sequestration. To be meaningful, information about cation concentrations would have to be combined with a full ion balance to include any species contributing to the weathering. Samples with high and variable solids content can be challenging to analyze by ICP-MS due to interferences from the sample matrix.

5. 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 (Jorat et al, 2022).

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 CO₂ sequestered.

6. 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 (HCO₃⁻) 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 (Manning et al. 2013; Haque et al. 2019).

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 CO₂ 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 CO₂ 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.

7.6. Supplementary examples of simulation & validation approaches

→ *This supplementary information presents two examples of currently (2022-11) utilized ERW models. The information in this chapter is provided for education purposes only, and no recommendation for the utilization of any particular model should be inferred. The field of ERW modeling is developing rapidly, and the suitability of a particular model for a particular project must always be analyzed on a case-by-case basis.*

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

Here, a **simulation** refers to a set of equations implemented in computer software that is utilized to make a prediction depending on a certain number of input parameters. A simulation provides several outputs, one of which is an estimate of the amount of carbon stored for a determined amount of time. 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. Depending on the simulation approach selected, several different quantities can be measured for validation purposes (see, Section 7.5).

The Kelland model and simulation approach

- The **Kelland model** is a one-dimensional (1D) soil geochemical reactive transport soil process model to estimate CO₂ removal for basalt weathering over multi-decadal timescales. The model was published in open-access peer-reviewed journals. First in Kelland et al. (2020), and further developed in Lewis et al. (2021) and Vienne et al. (2022).
- 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.
- The main model **inputs** are: basalt mineralogy, particle size, surface area, and density of application; site-specific soil chemical and physical parameters; and 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.
- 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 CO₂ dissolved in rainwater or irrigation water, as well as CO₂ from respiration of organic matter within the soil profile; progressive

reduction in silicate mineral reactive surface area with dissolution.

- 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^{2-}). 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 model has been initially **validated** using soil pot trial experimental data (Kelland et al., 2020; Vienne et al., 2022), and further model validation is in progress as new data becomes available.

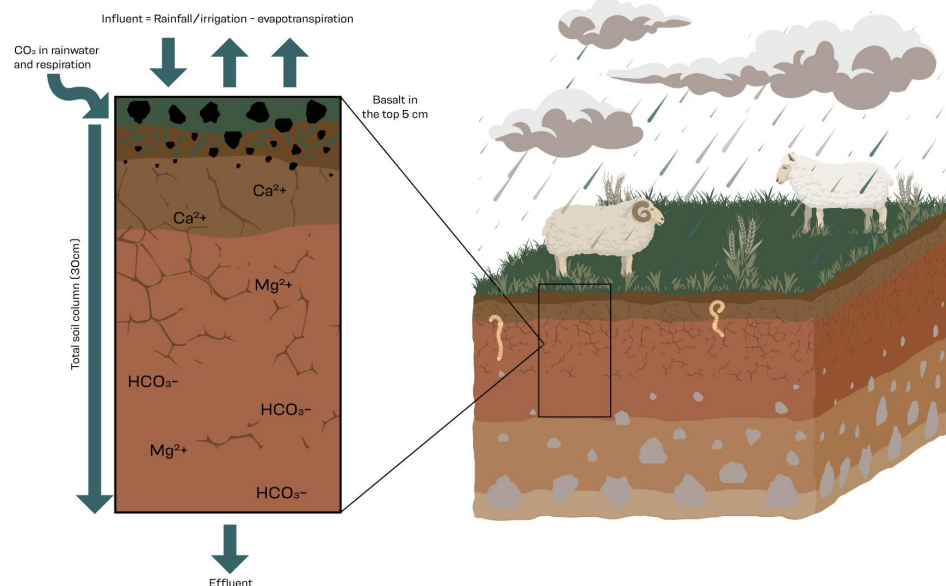


Figure 4. Visualization of the “Kelland” model.

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.

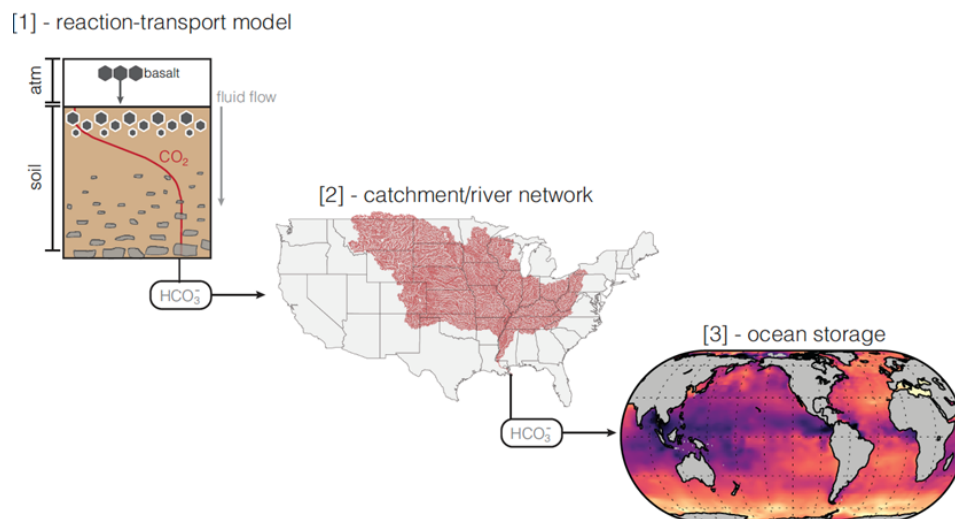


Figure 5. Overview of the three (3) components of the Lithos enhanced weathering modeling framework that allows for estimates of carbon capture during weathering and the amount of carbon storage in rivers and the oceans over a given timeframe.

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 **S**oil **C**ycles of **E**lements simulator for **P**redicting **T**ERrestrial regulation of greenhouse gases (Kanzaki et al., 2022).²⁷

- 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.
- The main model **inputs** are: **(1)** rock and mineral feedstock application rates and the physical characteristics (particle size distribution, surface area, mineralogy); **(2)** climatological boundary conditions (such as surface temperature, water infiltration rate and soil water content); **(3)** an initial soil mineralogy and organic carbon concentration based on either soil type and/or the chemical composition of the soil; **(4)** 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; **(5)** time varying soil mixing regimes (such as natural bioturbation or

²⁷ <https://gmd.copernicus.org/articles/15/4959/2022/>

tilling); and **(6)** crop type and fertilization protocol.

- The model **accounts** for background and enhanced weathering and other biogeochemical **processes** including: **(1)** dissolution and formation of mineral phases; **(2)** dissolved ion transport; **(3)** plant uptake and sorption; **(4)** CO₂ introduction into the soil profile through gas phase transport and organic carbon respiration; **(5)** dynamic re-equilibration of the carbonic acid system; **(6)** organic acid production and destruction; **(7)** grain-size driven changes in feedstock surface area as weathering proceeds; and **(8)** modulation of soil carbonate chemistry by initial ('residual' acidity) and sorbed cations.
- 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).
- 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 (Kanzaki et al., 2022).

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.²⁸ These models track the products of enhanced weathering in surface waters and in the oceans on a decadal to thousand-year time scale.

- 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.
- The main model **inputs** are: **(1)** a high-resolution digital elevation model that is used to specify the catchment for the site of enhanced weathering; **(2)** 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; and **(3)** a greenhouse house gas emissions trajectory over a thousand-year time interval.
- The model **accounts** for: **(1)** dynamic re-equilibration of the carbonic acid system in river/stream waters and surface oceans; **(2)** formation of clay and carbonate mineral phases (and associated CO₂ re-release) during transport; and **(3)** mixing of

²⁸ <https://bg.copernicus.org/articles/4/87/2007/>
<https://gmd.copernicus.org/articles/13/5687/2020/>

different water masses (both in the river network and in the oceans).

- 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.
- 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.
- 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.

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END OF METHODOLOGY