Global Rock C-Sink

Guidelines for the Certification of C-Sinks form Enhanced Rock Weathering Projects in Croplands

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Preface

The climate crisis requires rapid action to stop atmospheric CO_2 levels from rising any further. In addition to fully reducing all avoidable greenhouse gas emissions, negative emission technologies must also be developed and rapidly scaled to create C-Sinks where carbon is stored outside the atmosphere. There will be need to a portfolio of methods to increase speed, minimize risk, and generate locally adapted solutions with co-benefits. Enhanced rock weathering (ERW) will be part of this carbon dioxide removal (CDR) portfolio, however is currently a particular case for two reasons:

1) Rock powder is already used by some farmers to improve soils. Thus, it is at least to some extent a traditional approach with considerable co-benefits. However, the technology is not yet as advanced in terms of CDR as, for example, PyCCS and the use of biochar. A generally accepted method, e.g. through scientific peer review, for ex-post quantification CDR ,through ERW does not yet exist (as of December 2023).

2) Enhanced rock weathering creates costs for procurement and application of rock powder, i.e. most costs are incurred at the beginning of the project. In addition, the production, transport and application of rock flour require energy and thus cause greenhouse gas emissions. For certification as a C-Sink within the Global C-Sink framework, this must be offset instantaneously by suitable, high-quality and thus also expensive C-Sink certificates. This further increases the upfront costs.

In 2022/2023, **The Carbon Drawdown Initiative**, the **Ithaka Institute for Carbon Strategies** and **Carbon Standard International** run a prototype project involving nine farmers that applied a total of 1200 t of basanite rock powder. This project aimed at testing feasibility and economics of ERW in praxis. It was certified according to Global Rock C-Sink (Version 1) which certified the Rock C-Sink potential, but not yet actual CDR. Based on the experience of the prototype and the above mentioned consideration, the present guidelines have some special features:

1) Carbon Standards International does not yet offers certification according to present guidelines, up until a method to quantify CDR is admitted.

2) To enable ERW projects now, the present guidelines provide a methodology defining sustainable and eligible ERW projects and the appropriate self-documentation of the implementation of projects implemented to this standards.

3) Once a method for quantification of ERW based CDR is available, validated and accredited by Carbon Standards, the method can be employed to documented ERW projects, converting the C-Sink potential of the projects to certified carbon removals.

Goal and Scope

The goal of Global Rock C-Sink is to enable the application of rock powder for carbon dioxide removal (CDR) by enhanced rock weathering (ERW) by documenting and certifying that.

1) A defined amount of rock powder
2) With known properties
3) Was applied to a specified piece of land,
4) In a manner that is agronomically sound and avoids any negative impacts on the environment,
5) Which caused a known amount of greenhouse gas emissions (carbon expenditures) that to be compensated by high quality C-Sink certificates to assure that
6) The known amount of carbon dioxide removal, upon complete weathering of the rock (C-Sink potential), will be a net negative emission.

Thus, the documentation and certification process includes:

A) Analysis of the rock,
B) Analysis the soil,
C) Acquisition of climate data regional to the project area
D) Auditing of the source of the rock powder, i.e. the mine and
E) Auditing of the C-Sink Manager
F) Rules to store back-up samples of soil and rock powder for future analysis,
G) A simplified life cycle assessment of the overall project,
H) Registration of the certified C-Sink in the Swiss Carbon Register

Key figures of the certificate are the CDR_{max} and the potential permanent C-Sink that can be achieved by the project in the long-term. A method to quantify the actual weathering, i.e., the weathering rate, is not part of this guidelines. Instead, criteria are defined to accredit novel methods based on well-justified requests to Carbon Standards. Thus, under the current version of Rock C-Sink, actual CDR cannot be certified. The Global Rock C-Sink will allow retroactive conversion of C-Sink potential to certified C-Sinks, from projects presenting approved self-documentation once a method for quantification actual CDR has been accredited by Carbon Standards and full certification has been installed. C-Sink certificates may than be traded and used analogously to certificates from other Global C-Sink certification frameworks. However, retroactive certification of projects / rock powder applications that have not been documented according to the present guidelines is strictly excluded.

Content

1 Introduction

Natural weathering of silicate rocks is sequestering substantial amounts of atmospheric CO_2 in the form of dissolved inorganic carbon (DIC) that may eventually reach the ocean or precipitate as carbonate by biotic or abiotic processes. Diluted inorganic carbon and other alkaline products, originating from the weathering of silicate rocks, ultimately contribute to ocean alkalinization, a natural process sequestering 0.5 Gt CO_2 year^{-1} (Renforth and Henderson, 2017). Hence, silicate rock weathering is a major feedback mechanism for atmospheric CO_2 and impacts the climate on geological timescales. These natural weathering processes can be enhanced through the comminution of silicate rocks to increase their reactive surface areas and exposing them to an environment favourable for weathering e.g., the plant root zone (rhizosphere) or ocean's surface waters (Hartmann et al. 2013). Such practice is referred to as enhanced (rock) weathering (EW or ERW), which is regarded as a promising negative emission technology (EASAC, 2018). A resource base of 90.000 Gt of suitable rock material is theoretically available, holding the potential of sequestering CO_2 equivalent to 700-years of global emissions (Bide et al., 2014). Certainly not all resources can be exploited, due to economic and ecologic constraints, nor can rock powder be reasonably applied to the corresponding extent.

Still, the relevance and applicability of ERW for climate change mitigation is high. If ERW is implemented globally, CO_2 sequestration potentials may reach 1-4 Gt CO_2 year^{-1} (Köhler et al., 2010; Strefler et al., 2018; Beerling et al., 2020). Partly, underutilized resources such as mine tailings (powder-like by-products from rock mining) can be utilized for ERW, which may reduce costs and process emissions (Kelland et al., 2020; de Oliveira Garcia et al., 2020). Enhanced rock weathering is not competing for land, instead, ERW is generating agricultural co-benefits by supplying essential macro- and micronutrients, liming effects, and silicon fertilization. Thus, ERW may support plant health and replace external inputs, and thus also abate associated emissions (Amann and Hartmann, 2019; Kelland et al., 2020; Lewis et al., 2021). The addition of primary minerals and the consecutive formation of secondary clays may stabilize native soil organic carbon (Singh et al., 2018; Bai and Cotrufo, 2022). Lastly, alkaline reaction products reaching waterbodies can actively counteract ocean acidification (Hartmann et al., 2013), supporting marine biota and promoting additional oceanic carbon drawdown.

Silicate weathering under natural conditions primarily results in the formation of bicarbonate, a form of DIC which doesn't directly exchange with the atmosphere. The mean residence time of bicarbonate in the ocean is in the order of 1.000-10.000+ years (Rau et al., 2011; Hartmann et al., 2013; Renforth and Henderson, 2017), thus representing a C-Sink of high persistence.

However, until today there is no generally accepted method for monitoring, reporting and verification (MRV) of ERW projects and challenges to accurately account ERW facilitated carbon dioxide removal (CDR) prevail (Amann and Hartmann, 2022; Calabrese et al., 2022).

The present guidelines provide a methodology for the monitoring, reporting and verification of rock powder application to croplands. This includes:

- The documentation of the **rock powder application** from rock mining to the actual spreading. Legality, environmental safety, work safety and agronomic appropriateness are ensured.
- The calculation and documentation of the **Rock C-Sink potentials** i.e., the amount of carbon that will be removed from the atmosphere at the long term and will be stored as inorganic carbon.
- The calculation and external **compensation of the carbon expenditures**, i.e. the emissions caused by the production, procurement and application of the rock powder.
- Criteria to admit novel methods to quantify actual CDR based on measurements and modelling.

Since full certification cannot be offered at present (see "Preface" and "Goal and Scope"), and the associated cost of third-party certification, including compensation of carbon expenditures, is disproportionate to the current value of the certificates, (as long as there is no method to calculate the actual CDR), we offer the option for **approved self-documentation** to allow **retro-active certification** based on this data.

The maximum CDR that will be achieved by complete weathering of a rock (CDR_{max}) can be quantified based on the elemental composition of the rock. The amount of long-term carbon storage that can be achieved by complete weathering can be calculated based on well-grounded, conservative assumptions on carbonate precipitation (cf. chapter 4) that are summarized in safety factors to be multiplied with CDR_{max}. However, high, uncertainty remains regarding the speed, i.e., the field specific rate of the weathering reactions depending on both rock mineralogy and site-specific environmental conditions. As of today, accurate modelling or measurement of ERW under real-world conditions is still not demonstrated. As a result, weathering rates and thus both actual weathering and actual CDR cannot yet be certified for ERW.

Until the validation and accreditation of a method to quantify or model the actual weathering (cf. chapter 7), the present guidelines only define and document the sustainable application of rock powder and calculate the Rock C-Sink potential to enable prepurchase agreements and investments. **The Rock C-Sink potential must not be employed or sold for direct CO_2 compensation or any other climate service.**

ERW is generally a safe climate technology that poses hardly any risks to humans or the environment. The trace elements ("heavy metals") contained in the rock are the most relevant risk, yet it can be controlled by the selection of the rock type (limit values for the content of trace elements), maximum rock application rates and limit values for background concentrations of trace elements in the soil prior to rock powder application. It is imperative that cropland based ERW applications follow national regulations on fertilization and soil protection and only create positive effects to the agronomic system. Rock powder applications can fully be acknowledged as a beneficial agricultural practice – not as a CDR focused burden to be carried by the farmers and the food system.

The energy required to produce rock powder (mining, milling) is small but relevant, while transport emissions can be more substantial. The present methodology will address this issue by distinguishing between **mine tailings** and **rock powder explicitly produced for ERW** purpose. For both material streams the full set of relevant production, transport and application emissions attributed to the rock powder must be quantified and compensated for. Thus, the present method only certifies real (net) C-Sinks created by climate neutral value chains. Operations emitting more. – or only little less - CO_2 than they are sequestering, are rendered uneconomic and fail to enter the carbon market.

Rock C-Sinks created through ERW build up over a considerable time horizon, with the ocean being the final reservoir of sequestered atmospheric carbon. The longer the considered time horizon, the higher the likelihood that the initial rock dissolves and generated DIC is reaching a stable reservoir, e.g., the ocean. This is a particular feature of ERW technology: The longer the considered time horizon, the lower is the uncertainty and risk.

2 Rock properties

In geology, a mineral is defined as a solid chemical compound with specific chemical composition and crystalline structure. Materials generically referred to as rocks are typically a conglomerate of different minerals, thus multi mineral assemblage. Based on their formation pathway rocks can broadly grouped into three classes: 1. Sedimentary rocks, e.g., sandstone or limestone, resulting from accumulation and compaction of sediments, a process called diageneses. 2. Metamorphic rocks, e.g., gneiss or marble, resulting from the exposure of any kind of rocks to pressure and/or heat as the result of tectonic processes (metamorphism) - and 3. Igneous rocks, e.g., granite or basalt, resulting from crystallization of magma in the upper mantle or crust, or at the surface following volcanic events. Rock materials suitable for ERW purpose, are typically silicate rocks, found in the 3rd group. Silicate rocks show silicon dioxide (SiO_2) concentrations of > 40 % by weight, in the form of silicate-group bearing primary minerals. At SiO_2 concentrations of < 52 % or < 45 %, they are classified as mafic/basic, or ultramafic/ultrabasic, respectively. These classes usually feature high concentrations of calcium, magnesium, and iron. Due to the high content of these divalent cations, they are most effective for ERW applications. Some rocks matching this category are colloquially known as basalt, gabbro, dunite, diabase or dolerite.

2.1 Mineralogy

Not all rock types are suitable for ERW applications. As the colloquial names of rock types are only poorly backed by coherently constrained, chemical definitions, the present guidelines abstain form a *positive list* of admitted rock types. However, to guarantee effectiveness and safety of cropland based ERW projects, the present guidelines will define thresholds in mineralogy and elemental composition, which must be met by the rock powder product, to be rendered admissible for C- sink certification under the present guidelines and embracing national laws.

Generally, the solubility of a mineral depends on the degree of silica polymerization (prevalence of strong Si-O bonds), which, e.g., is high in the mineral quartz and low in the mineral olivine. Therefore, different primary minerals show diverging dissolution behaviours even under the same environmental conditions (Renforth and Campbell, 2021). While the actual weathering rates are specific to site conditions, a ranking of relative weathering speeds can be established through a comparison under standard conditions (25°C and pH 6) as conducted by Goldich (1938) (Fig. 1). Based on these standardized comparisons, minerals can be grouped based on high, intermediate, or low solubility. For a rock to be admissible under the present guidelines, **a mass fraction of ≥ 50% must be composed of silicate minerals expressing a high solubility, namely Olivine, Plagioclase, Pyroxene, and K-feldspar.** Criterion fulfilment is judged based on the results of an X-ray diffraction, which allows a bulk mineralogical analysis to quantify ∑ (Olivine, Plagioclase, Pyroxene, K-feldspar) as described in Annex 10.1.1.

Further, most igneous rocks are silicate rocks, but they may contain a minor fraction of carbonate minerals. Based on the stoichiometry of the weathering reaction of carbonate minerals, the latter process cannot be rendered a net C-Sink in the long term. If the carbonate mineral pools are small, these effects are negligible. If the carbonate pool is exceeding 2%, it needs to be accounted for through the deduction of the carbonate minerals from the initial mass balance and elemental composition. The carbonate fraction is determined via bulk mineralogical analysis by X-ray diffraction, as described in Annex 10.1.1.

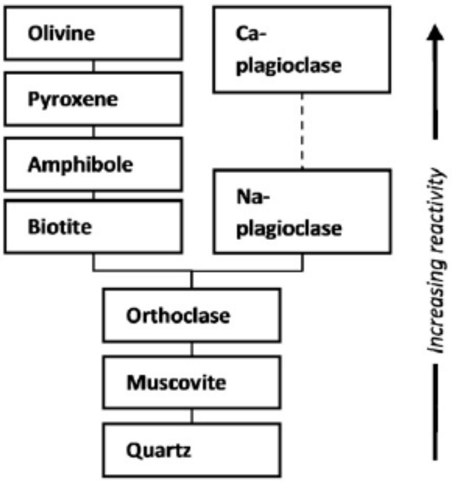

Figure 1: Relative solubility of different mineral classes. Figure adopted from Goldich (1938) and Renforth (2012). Mineral groups at the top have a low degree of silica polymerization and dissolve fast, mineral groups at the bottom have a high degree of silica polymerization and dissolve slower.

2.2 Elemental composition

The elemental composition of a given rock and respective rock powder is determining both its value as fertilizer and soil improver as well as its inherent theoretical CDR capacity (CDR_{max}). Also, trace element content is an important factor to ensure the safety of ERW.

2.2.1 Main elements: The CDR capacity of a rock

The CDR_{max} of a specific rock is referring to the mass ratio of CO_2 transformed into bicarbonate after complete rock dissolution, based on the initial rock dry weight. For example, a CDR_{max} of 0.418 indicates that 1 t rock can theoretically sequester a maximum of 0.418 t CO_2 when 100-% weathering is achieved. For suitable igneous silicate rocks, the CDR_{max} may be in the range of 0.2-1.2 (Rinder and Hagke, 2021).

Weathering refers to the reaction of a solid mineral (as part of a rock) with water and CO_2. In the first step, the CO_2 dissolves in water and forms carbonic acid (H_2CO_3). The acid is very weak and dissociates almost instantly such that concentration of true carbonic acid is 3 orders of magnitude lower than that of the deprotonated species, bicarbonate (HCO_3^-) and carbonate ion (CO_3^{2-}). The dissociated protons (H^+) react with the primary mineral, which disintegrates into weathering products. This process is called hydrolysis. At the end of this reaction the primary mineral is weathered into a secondary mineral (typically an aluminosilicate clay mineral), dissolved, basic metal cations (e.g., Ca^{2+}or Mg^{2+}) and DIC mainly in the form of bicarbonate anions (HCO_3^-). The negatively charged bicarbonate is unable to interchanges with the atmosphere and kept in solution along with a charge equivalent load of cations.

Chapter 2.2.1 - Box 1
Simplified weathering reactions

Weathering of the primary silicate mineral olivine (forsterite):

$$Mg_2SiO_4 + 4CO_2 + 4H_2O \rightarrow 2Mg^{2+} + 4HCO_3^- + H_4SiO_4$$

The weathering of this mineral releases 2 moles of divalent magnesium cations and creates charge equivalent 4 moles of bicarbonate anions.

Weathering of the primary silicate mineral albite

$$2NaAlSi_3O_8 + 2CO_2 + 11H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2Na^+ + 2HCO_3^- + 4H_4SiO_4$$

The weathering of this mineral releases 2 moles of monovalent sodium cations and creates charge equivalent 2 moles of bicarbonate anions.

Overall, during mineral weathering one mol of bicarbonate is formed and stabilized per released charge equivalent of available cations (Table 1). Each mol of bicarbonate originating from this reaction process is equivalent to one mol of CO_2 consumed and sequestered from the atmosphere (Lewis et al. 2021).

Thus, CDR_{max} is a function of the metal cation flux released from the weathering process. The CDR_{max} can be calculated based on the absolute metal content of the given rock multiplied with the cation specific valence, which is present once the metal is released to the ambient solution in ionic form (Table 1) .

Table 1: Geogenic metal ions

Metallic Element	Ionic Form and Valence
Calcium	Ca^{2+}
Magnesium	Mg^{2+}
Potassium	K^+

Sodium	Na^+
Manganese	Mn^{2+}
Aluminium	Al^{3+}
Iron	Fe^{2+}/ Fe^{3+}
Titanium	Ti^{4+}

There are different concepts, representing different degrees of conservativeness, to calculate the CDR_{max}. For some fast-weathering silicate rocks, only $\sum (Ca^{2+}, Mg^{2+})$ is considered (Renforth, 2012). For other rocks comprising relevant pools of K and Na (e.g., basalt) these elements are also considered, here the CDR_{max} is calculated based on $\sum (Ca^{2+}, Mg^{2+}, K^+, Na^+)$ (Tole et al. 1986). The formula may be extended to $\sum (Ca^{2+}, Mg^{2+}, Mn^{2+}, K^+, Na^+)$ when high concentrations of Manganese are present in the given rock. All the above summations relate to the realistic assumption of an incongruent dissolution of the primary aluminosilicates, preserving the aluminium (same as iron and titanium) in a solid phase of secondary minerals, i.e., not releasing the latter metals as aqueous cations (Rinder and Hagke 2021). On geological timescales, also secondary aluminosilicates may partly be subject to dissolution, releasing aluminium, iron, and titanium. Minor contents of metallic trace elements are not included here. Considering the composition of common igneous rocks and considering the time horizon relevant for mitigation of anthropogenic climate change, the present guidelines deploy the standardized formular as per equation **(1)** (modified from Renforth et al. 2012).

Most contemporary research projects employ a variation of this well-established formula. However, it is hypothesized that weathering of primary minerals, does not lead to a full mobilization of elements. A fraction will be embedded in secondary clay minerals, still containing alkali metals (e.g., in the clay mineral montmorillonite). Until today the phenomenon of secondary mineral precipitation is not well constrained (Renforth and Campbell 2021; Campbell et al., 2022). To adequately account for this phenomenon a safety margin of 10% is deducted from CDR_{max}. Results will be rounded to three decimals providing an accuracy of 1 kg CO_2 per t $rock^{-1}$.

Equation (1):

$$CDR_{max} = \frac{MCO_2}{100} * \left(\frac{\%CaO}{MCaO} + \frac{\%MgO}{MMgO} + \frac{\%K_2O}{MK_2O} + \frac{\%Na_2O}{MNa_2O}\right) * 2 * 0.9$$

CDR_{max} *= ratio of sequestered CO_2 upon complete weathering, to initial rock weight in t CO2 t^{-1} rock.*
M CO_2/CaO/MgO/K_2O/Na_2O *= Molar mass of oxides*
% CaO/MgO/K_2O/Na_2O *= Mass fraction of oxides as determined in X-ray fluorescence analysis.*
2 *= Multiplier accounting for composition of K_2O and Na_2O and the divalent of Ca^{2+} and Mg^{2+} cations*
0.9 *= Safety margin to account for incorporation of relevant metals into secondary clay minerals*

Note: The content of major elements such as Ca, Mg, etc. is usually expressed as oxides (CaO, MgO, etc.). However, this does not mean that the elements are present as oxides or react to form oxides. This is just a convention in geology and analytical chemistry.

Chapter 2.2.1 - Box 2
Calculation of the CDR_{max} for a basalt rock

$$CDR_{max} = \frac{MCO_2}{100} * \left(\frac{\%CaO}{MCaO} + \frac{\%MgO}{MMgO} + \frac{\%K_2O}{MK_2O} + \frac{\%Na_2O}{MNa_2O}\right) * 2 * 0.9$$

$$CDR_{max} = \frac{44.01}{100} * \left(\frac{11.8}{56.08} + \frac{9.95}{40.03} + \frac{2.75}{94.2} + \frac{2.46}{61.98}\right) * 2 * 0.9$$

$$CDR_{max} = 0.418\ t\ CO_2\ t^{-1} rock$$

Upon well-justified request to Carbon Standards equation **(1)** may be modified or extended for the application to discrete rock powder production batches, showing relevant concentrations of other metals.

2.2.2 Nutrients and trace elements

Rock powders contain a range of elements including macro- and micronutrients, essential for crop growth and health. However, some rocks may also contain trace elements that are environmental pollutants.

Rock powder for the deployment in croplands must be safe and beneficial for agroecosystems and must adhere to all applicable regulations on fertilization and soil protection. To be considered under the present guidelines, the rock powder must be analysed for the following nutrients:

- Nitrogen (N)
- Phosphate (P)
- Potassium (K)
- Magnesium (Mg)
- Sulphur (S)
- Boron (B)
- Copper (Cu)
- Zink (Zi)
- Cobalt (Co)

- Selenium (Se)
- Chlorine (Cl)
- Alkaline Components (calculated as CaO equivalents)

And for the following trace elements:

- Arsenic (As)
- Lead (Pb)
- Cadmium (Cd)
- Chromium (Cr)
- Nickel (Ni)
- Mercury (Hg)
- Thallium (Tl)

The analytical methods, product labelling thresholds and limit values for each parameter are given in Annex 10.1-10.2.

Natural mineral rock powders do not contain organic contaminants, thus an analysis for organic contaminants is not mandatory under these guidelines.

2.3 Rock powder characteristics

Grain size and grain size distribution are decisive factors for the determination of the rock weathering rates and boundaries must be defined here.

Generally, rock powders in a particle range of 0-2000 µm are admissible. A margin of 5 wt% > 2000 µm can be tolerated. This mass will be added to the mass of the largest sieve fraction (see characterization of particle distribution, Annex 10.1.1). Any mass fraction exceeding the given threshold and tolerance margin must be deducted from the total rock powder mass applied to a given field so that only the size fraction < 2000 µm (+ 5 wt% margin) is considered for calculation of the C-Sink potential and for certification.

Defining a rather broad admissible particle size range, serves the purpose, that also mine tailings (powdery by-products of rock mining) can be deployed under the present guidelines. Mine tailings are often comprised of powder like particles, however since they represent a mining by-product the particle size distributions are not intentionally controlled and may contain larger particles. Nevertheless, mine tailings represent an abundant resource that may be exploited for ERW purpose without causing additional emissions from mining and milling. Mine tailings left unused will not weather to a relevant extent, as the chemical conditions in a pile of mine tailings will not favour weathering.

The particle size distribution must be determined according to the method described in Annex 10.1.1. This includes the fractionation into at least five[1] size classes using sieving procedures.

The mean moisture content of the rock powder at factory gate should be measured and indicated on the delivery note. Alternatively, a moisture content of 10%, will be assumed.

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[1] An optimized number of fractions to be characterized is subject to ongoing research. There are trade-offs between analytical costs and resolution of data - and thus accuracy of potentially employed models. Upon the next revision of this guidelines the number of required fractions will likely be corrected downwards.

3 Rock powder application to cropland

For successful and safe ERW projects not only suitable rock feedstock must be selected, but also land units being subject to rock powder application must fulfill a set of minimum requirements to facilitate ERW in the long term. Only in combination, suitable rocks, and land units of favorable agroclimatic conditions can ensure successful and safe ERW operations.

3.1 Admissibility of the land

The present guidelines define land characteristics, to render a location eligible for ERW project certification.

3.1.1 Land use

Only rock powder applied and incorporated into the topsoil of an agricultural system can be certified according to the present guidelines. The product approval and material safety regulations considered in the above chapters exclusively refer to products deployed in the agricultural sector. Rock powder applications to forest land and nature conservation areas and beaches are not covered by the present guidelines but may be approved on a case-by-case basis upon submission of a well-reasoned request to Carbon Standards.

Conservation agriculture and grassland: Rock powder can be applied to agricultural systems employing reduced-tillage, conservation-tillage or no- tillage regimes. Minimizing or reducing tillage is a crucial part of sustainable agricultural management of topical soils, reducing soil organic carbon mineralisation and erosion (Thierfelder 2017; 2021). Nevertheless, this practice cannot ensure that the rock powder will enter the rhizosphere promptly after application and thus be exposed to the desired conditions (high CO_2 partial pressure, moisture) for weathering. Notwithstanding, the C-Sink potential can be certified in the same manner. The actual CDR, however, can be quantified when an accredited method accounts specifically for this mode of rock powder application e.g. by considering the time needed for the rock powder to enther the rhizosphe.

3.1.2 The decadal aridity index

Weathering reactions such as the conversion of solid mineral species into dissolved aqueous species is governed by their saturation index in the soil solution. If the soil solution is saturated with respect to a particular mineral phase, the mineral dissolution stops.

The anticipated long-term storage of DIC in sub-soil and open water bodies assumes, that a net downward movement of soil water takes place, constantly or intermittently draining the rhizosphere.

Both prerequisites, the replenishment and desaturation of the soil solution - and the net downward movement of soil water can well be met, if the annual precipitation (equivalent to potential infiltration of water into the soil in mm) is larger than the annual potential evapotranspiration (equivalent to potential soil water loss). The ratio of precipitation to evapotranspiration is given as the aridity index of a region. If the aridity index (Ai) is >1 the precipitation is larger than the potential evapotranspiration. The environmental program of the United Nations defines regions with Ai > 0.65 as humid (Zomer and Tarabucco, 2019).

The decadal Ai determines the prevailing ratio between evapotranspiration and precipitation of a region, considering a data series spanning the last 10 years before rock powder application. Databases for aridity indices can be directly accessed online, or the aridity index can be calculated from primary data. The decadal Ai is calculated by dividing the cumulative precipitation over the 10 before rock powder application by the cumulative potential evapotranspiration over the 10 years before rock powder application. Hereby the current calendar year is omitted, due to data availability constraints. Depending on data availability, generic, or crop/soil specific evapotranspiration rates measured or modelled for the region can be employed.

For project locations in the temperate zones, showing discrete cropping seasons potentially bridged by cover crops, potential evapotranspiration measured or modelled for grassland may be deployed. In any case, the same type of plant cover can be assumed for the whole year.

Equation (2):

$$Decadal\ Aridity\ Index = \frac{10 year \sum Precipitation}{10 year \sum Potential\ Evapotranspiration}$$

To be admitted under the present guidelines the decadal aridity index of a given location/region must be ≥ 0.65.

Data can be obtained from regional measuring stations or regional- and interregional models. The latter are provided by the European Union and national or regional authorities. For each location of rock powder application, agroclimatic data of the nearest measurement station, reference location or grid cell must be collected. The certification body must verify the source of the data and its plausibility.

Chapter 3.1.2 - Box 4
Calculating the decadal aridity index Ai_{dec} for a central European location

For a reference location in Ohlsbach, in the Ortenau district in Germany, the sum of monthly precipitation from January 2012 to December 2021 is 9660.4 mm and the sum of evapotranspiration (modelled for *grassland*) from January 2012 to December 2021 is 7508.6 mm. All data was sourced from the German meteorological service database (DWD, 2022)

$$Ai_{dec} = \frac{9660{,}4}{7508{,}6} = 1.29$$

The region has a decadal aridity index > 0.65 and qualifies for ERW in cropland applications according to the present standard.

3.1.3 Soil pH

Maximum Soil pH: Basic and ultra-basic igneous rocks, the most suitable feedstock for ERW application, contain alkaline compounds, thus the rock powders are functioning as a liming agent, increasing the soil pH. The crop-dependent ideal soil pH for agricultural operations is 6.5 - 7.0. More acidic or more alkaline soil conditions lead to reduced nutrient availability to crops. Further, strongly alkaline soil conditions may foster the natural formation of secondary clays and formation of carbonate minerals, impeding the realization of a rocks CDR_{max}. Thus, an upper limit to the baseline soil pH (before rock powder application) of 7 (+0.3 units' tolerance above neutrality) is defined here.

Minimum Soil pH: In low pH ambience it is likely, that weathering also occurs due to the reaction of minerals with non-carbonic acids, such as nitric acid. A weathering reaction with acids other than carbonic acid will also disintegrate the primary minerals, however, will not lead to CDR. It is argued that already in soils with pH <6.3 a correction of CDR rates may be required and soils with pH <5.2 are likely unsuitable candidate for ERW based CDR (Dietzen and Rosing 2023). Until this phenomenon is further constraint the Global Rock C-Sink applies a lower pH threshold of 5.2 for land eligibility. This threshold may be lowered or removed in the future.

Thus, a land units initial soil pH must be ≥ 5.2 ≤7.3 to be admissible under the present guidelines. The topsoil's pH (0-30cm) must be measured in diluted $CaCl_2$ solution according to the method described in Annex 10.1.

3.1.4 Unsealed soil

Mineral weathering is a relatively slow process occurring over years and decades. It should be ensured that the land unit is providing environmental conditions favourable for ERW also in the future. For this reason, the present guidelines only permit ERW projects on land classified as agricultural land or land where other regulations ensure that it will not be for the foreseeable future (decades), such as by converting it to developed building land, roads or other infrastructure.

The land must not be classified as potential construction ground according to the authorities regulating land use changes or regional representations of the state cadastre offices. It must be ensured - as much as possible - that the land use class is not converted to urban use – potentially associated with surface sealing and exclusion of percolating water – within the respective time horizon required for the realisation of the certified C-Sink potential.

If the respective area is subject to surface sealing past rock powder application, but prior to realizing the certified C-Sink potential, this must be indicated to the certification body instantly.

If all or part of the Rock C-Sink Potential is converted to a C-Sink Certificate in the future by measurement or modelling, it must be demonstrated, for example, by a georeferenced photograph or by satellite imagery, that the area remained unsealed.

3.1.5 Background concentrations of trace elements

Rock powders may contain small but relevant loads of undesired trace elements. Only rock materials, which have elemental composition that adhere the respective fertilizer regulations are allowed to be deployed under the present guidelines. Additionally, the present guidelines only admit land units with low background concentrations of trace elements not exceeding the following precautionary limits (mg kg^{-1} soil dry weight):

Table 3: Precautionary values for inorganic soil contaminants [mg kg^{-1} dry soil]

Soil Type	Cadmium	Lead	Chromium	Copper	Mercury	Nickel	Zink
Clay	1.5	100	100	60	1	70	200
Loam	1	70	60	40	0.5	50	150
Sand	0.4	40	30	20	0.1	15	60

Threshold values are in accordance with the German Federal Soil Protection Act (BBodSchv 1998, Annex 2.4)[2]. Adherence to the threshold values must be confirmed through the analysis of a representative soil sample drawn according to the soil sampling protocol in Annex 10.1.1 and analysed according to Annex 10.1.2. If additional thresholds based on national or regional regulations or good-agricultural practice must be respected, the C-Sink Manager and landowner must ensure appropriate rock powder application rates based on soil and rock powder characterizations. For certification according to the present guidelines, the soil analysis for background concentrations of trace elements can only be omitted, if the rock powder application does not exceed the permitted annual loads of trace elements per hectare as indicated in Table 4[3]

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[2] For soils of the soil type clay with a pH value of < 6.0, the precautionary values for cadmium, nickel and zinc as per the precautionary values of the soil type loam/silt shall apply. For soils of the loam/silt soil type with a pH value of < 6.0, the precautionary values cadmium, nickel and for zinc as per the soil type sand apply. The same corrections apply for lead thresholds in soils with pH < 5.0.

[3] This equals the "Zulässige zusätzliche jährliche Frachten an Schadstoffen" in the German soil proctection ordonance (BBodSchV, 1998, Annex 2.5)

Table 4: Permitted annual loads of trace elements [g ha^{-1} $year^{-1}$]

Trace Element	**Permitted Annual Load** [g ha^{-1} $year^{-1}$]
Lead	400
Cadmium	6
Chromium	300
Copper	360
Nickel	100
Mercury	1.5
Zinc	1200

3.2 Mode of rock powder application

Building on existing infrastructure, lime spreaders operated by GPS guided tractors have proven a suitable technology for rock powder application (Fig. 2). However, also other technologies that enable homogeneous distribution of the rock powder may be deployed.

To avoid particle drift and dust development the rock powder should not be applied when completely dry. Further, spreader applications should not be carried out if there is strong wind (< 5 m s^{-1} according to best management practice for spray applications).

Specific limit values, e.g., with regard to the necessary moisture content, and further guidelines for application are in preparation.

Figure 2: Rock powder application using a widely available lime spreader. (Photo: Matthias Huber of Lindenhof, Achern, Germany, 2022).

Weathering rates are expected to be highest in the rhizosphere. Thus, an active incorporation into the topsoil to 15-30cm by tillage or any other means of soil preparation is recommended.

However, acknowledging the ecological benefits of conservation tillage such an incorporation depth is not mandatory and depending on the climate (precipitation pattern) a minimum depth of 5-10 cm might be sufficient in some places. A self-propelled downward migration of particles, due to percolation, and bioturbation is expected in any scenario.

The method and/or depth of incorporation of the rock powder into the soil must be documented and indicated on the certificate. This may include surface application without further tillage or application under a mulch layer. This factor must be considered in the subsequent calculation of the C-Sink. However, we highlight that topsoil applications without consecutive active incorporation, e.g., application to grasslands or other to non-tilled systems (grassland, miscanthus, bamboo etc.) will require a deliberate method to quantify actual weathering rates. Models and methods based on data from experiments with rock powder incorporated into soil cannot be readily applied to projects without active soil management.

3.3 Maximum application rates

Rock powders contain nutrients in low concentrations, however due to large volume of rock powder application, it may still result in relevant loads. Thus, application quantities and associated nutrient loads must show conformity to applicable fertilizer regulations.

Of the major macro nutrients nitrogen (N), phosphorus (as P_2O_5) and potassium (as K_2O), N and K_2O are of no concern, as the nutrients are not a relevant constituent of rock powder (N) or not considered a risk for eutrophication and thus usually not subject to fertilizer regulations (K_2O).

If the present certification guidelines are deployed in a country imposing limits to nutrient loads applied to agricultural land, the farmer must be informed about the nutrient load contained in the applied rock powder in written form before the application. This is the duty of both the rock powder producer (declaration of nutrient content per ton on the delivery bill) and the C-Sink Manager (written information to the farmers about the nutrient load per hectare of the planned application, not applicable if the applying farmer and the C-Sink Manager are the same person).

The present guidelines recommend to not exceed a nutrient load of 30 kg P_2O_5 ha^{-1} $year^{-1}$ and define a definite limit to the applied P_2O_5 loads, equalling 50-% of the (estimated) field specific P_2O_5 requirement for the next 3 years.

Further, the present guidelines recommend an application limit of rock powder, containing not more alkaline compounds (as CaO, see Annex 10.1) than equivalent to 100% of the field specific liming requirement for the next 3 years.

The 3-year P_2O_5 requirement is calculated by the landowner (e.g., farmer) based on the anticipated crop rotation and before the rock powder application. The C-Sink Manager is obliged to request this data.

If the rock powder application regarding the P_2O_5 limit is exhausted in one year, at least two years must pass until the next certifiable rock powder application is permitted.

These recommendations and limit values are precautionary measures, ensuring flexible nutrient management to the farmers and securing their sovereignty in future decision making.

Chapter 3.3 - Box 5
Rock powder application limits and recommendations

In Germany, application limits to N and P_2O_5 apply (DüV,2017).

P_2O_5 applications shall not exceed a fields P_2O_5 requirement for the next 3 years.

A farmer planning to grow clover grass, oats, and grain maize in the next 3 years, calculated her field specific requirement to be 184 kg P_2O_5 ha^{-1} for the next 3 years. Her liming requirements for the next 3 years are 2000 kg CaO ha^{-1}.

A rock powder was analysed according to accredited methods indicating a N content of 0%, a P_2O_5 content of 0.44%, and alkaline compounds equal to 3% CaO.

The recommended rock powder application is 6.81 t ha^{-1} $year^{-1}$
(equivalent to 6810 kg rock ha^{-1} $year^{-1}$ * 0.44% P_2O_5 = 30 kg P_2O_5 ha^{-1} $year^{-1}$)

The maximum allowable rock powder application is 20.90 t ha^{-1}
(equivalent to 20900 kg rock * 0.44% = 92 kg P_2O_5 ha^{-1} = 0.5 * 184 kg P_2O_5 ha^{-1})

The exceeding of the liming requirement is of no concern.
(2 t CaO ha^{-1} / 0.03 t CaO t^{-1} = 66.66 t rock powder).

The farmer decides to apply 20.90 t rock powder ha^{-1} this year, covering 50% of her P_2O_5 requirements for the upcoming seasons. She records the application in the documentation of the farm nutrient budget.

The next certifiable application of rock powder can only be executed in the third year after applying these 20.90 t ha^{-1}, no rock powder application can be certified in first and second year after the present application.

4 Calculation of the Rock C-Sink potential: Accounting for downstream losses of dissolved inorganic carbon

To convert the CDR_{max} of a certain rock into the Rock C-Sink potential, i.e. the amount of carbon stored in the long-term as DIC as the result of a project, it has to be multiplied with the mass of rock that is applied and with safety factors that account for losses of DIC in the soil, during transport in freshwater environments, and in the sea. The Rock C-Sink potential is derived according to **equation (3):**

Equation (3):

$$\text{Rock C Sink Potential} = \text{CDR}_{\text{max}} * \text{m}_{\text{rock}} * \text{sf}_{\text{soil}} * \text{sf}_{\text{aquatic}} * \text{sf}_{\text{marine}}$$

CDR_{max} = theoretical CDR capacity, including a safety factor for metals retained in clay minerals (c.f. Chapter 2.2.1; equation 1)
m_{rock} = mass of rock powder applied in the field/project in tons dry weight
sf_{soil} = safety factor of 0.9 to cover calcium carbonate precipitation
$sf_{aquatic}$ = safety factor of 1
sf_{marine} = safety factor of 0.86, based on Lewis et al., (2021)

The safety factors are derived and calculated in the following subchapters.

Weathering of rock powder and dissolution of primary minerals removes CO_2 from the atmosphere by transforming it into dissolved bicarbonate. The present guidelines aim at the certification of the long-term stable mineral carbon species, as dissolved inorganic carbon in the ocean. Dissolved inorganic carbon comprises dissolved CO_2 and H_2CO_3, which are often summarized as CO_2*, as well as HCO_3^- and CO_3^{2-}. These inorganic carbon compounds are part of chemical equilibria collectively called the carbonate system:

A. $CO_2^*(aq) + H_2O(l) \Leftrightarrow HCO_3^-(aq) + H^+(aq)$

B. $HCO_3^-(aq) \Leftrightarrow CO_3^{2}(aq) + H^+(aq)$

C. $CO_3^{2-}(aq) + Ca^{2}(aq)^+ \Leftrightarrow CaCO_3(s)$

D. $H^+(aq) + OH^-(aq) \Leftrightarrow H_2O(l)$

(aq: in solution/dissolved, l: liquid, s: solid)

All species are dissolved, except calcium carbonate ($CaCO_3$), which precipitates as a solid. We focus on Ca and the formation of $CaCO_3$ as the only relevant process for precipitation. Its relative precipitation is four orders of magnitude higher than that of magnesium carbonate

($MgCO_3$), due to the larger size and coordination sphere of Ca (Schott et al., 2009). Formation of K_2CO_3 or Na_2CO_3 is barely observed under relevant conditions (Drever, 1988). The speciation of DIC in solution is determined by the pH (Fig. 3).

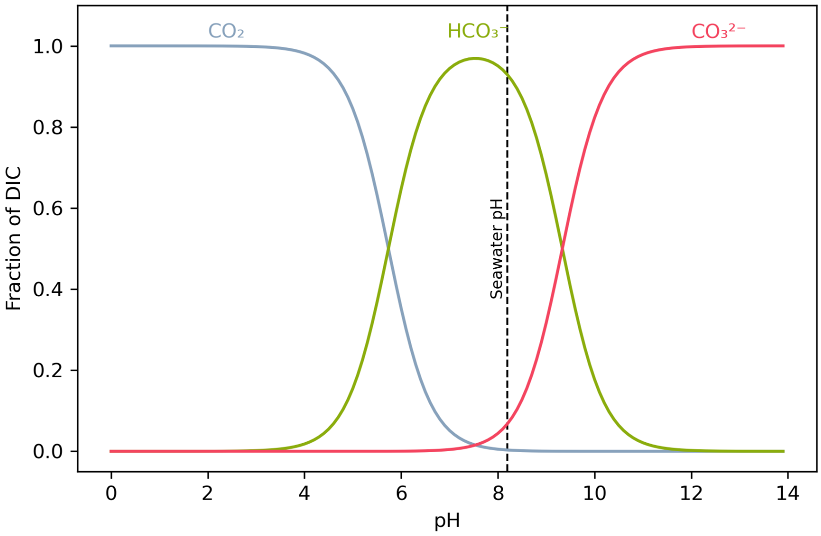

Figure 3: *The pH dependent equilibria of dissolved inorganic carbon species. Considering common pH ranges of ground- river or ocean water, the largest share of dissolved inorganic carbon will be present as bicarbonate. Bicarbonate can no longer directly exchange with the atmosphere.*

However, interactions in this system that may or may not result in carbonate precipitation in soil and water bodies are complex and also depend on other factors, including alkalinity, ionic strength, exchange of CO_2 with the atmosphere, uptake of CO_2 by photosynthetic organisms, and input of CO_2 via, e.g., decomposition of organic matter. When $CaCO_3$ precipitates (chemical equillibrium of reaction C moves to the right), not only CO_3^{2-} is removed, but also CO_2 is released, and the pH of the system is lowered. Thus, none of the following commonly used equations fully reflects the underlying chemistry:

$$Ca^{2+}\,(aq) + 2HCO_3^-\,(aq) \rightarrow CaCO_3\,(s) + H_2O\,(l) + CO_2\,(g)$$

$$Ca^{2+}\,(aq) + CO_3^{2-}\,(aq) \rightarrow CaCO_3\,(s)$$

We evaluate the likeliness of carbonate precipitation in soil pore water, groundwater, rivers, and the ocean (Fig.4) in the following subchapters and derive the safety factors used in Equation 3.

Once comprehensive, process based, hydrological models become available, which cover the soil- ground- and river water systems relevant to a certain project, the safety factors may be lowered or replaced through a case specific model run.

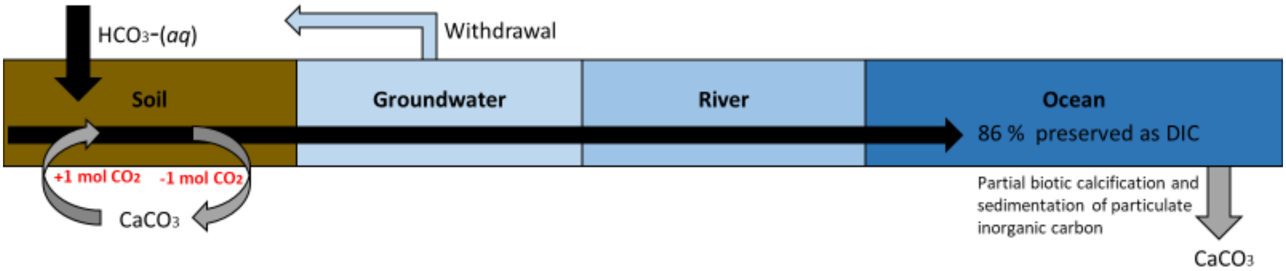

Figure 4: *Schematic pathway of HCO_3-(aq) from field to ocean. Considering soil solution, ground- and river water chemistry, substantial precipitation pf persistent calcium carbonate is neglectable.*

To illustrate, a C-Sink curve (modelled ex-ante, given as 100 data points generated by a modified shrinking particle model) must be corrected accordingly (Fig.5).

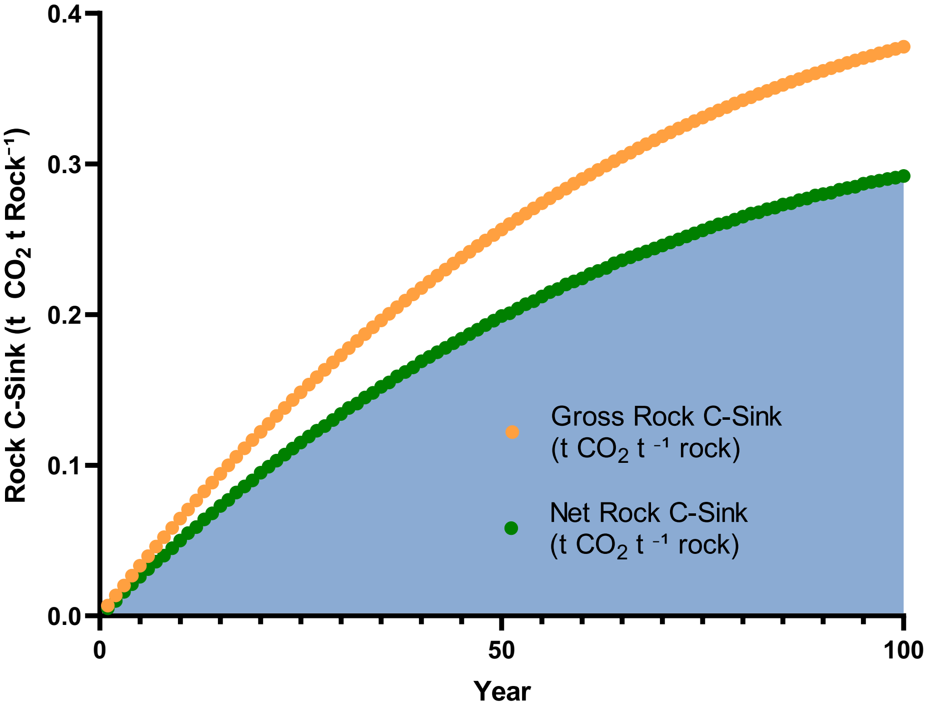

Figure 5 *Modelled C-Sink curve based on a methods described in Meyer zu Drewer et al. (2023) available on Zenodo, using the following parameterization: Particle size distribution = 0-2000 µm in 8 discretely characterized fractions, 0% rock moisture, specific surface area = 1.6-2 m²/g, maximum carbon dioxide removal = 0.418, soil pH = 6.6, soil temperature = 14.1 °C, soil CO_2 = 8.000 ppm, normalized net primary productivity = 0.6, valid month (no moisture limitation) =7. Corrected by a 10 % safety margin covering potential carbonate precipitation and corrected for the CDR efficiency of 0.86 considering the equilibrating aquatic/oceanic carbonate systems.*

4.1 Losses in soil pore water

If the soil solution is reaching a state of super saturation, DIC can precipitate as pedogenic carbonate (calcite) through the reaction with calcium cations (Haque et al., 2019; Haque et al., 2020; Kelland et al., 2020). As such reactions can occur throughout the soil profile, both during vertical or lateral flow of the soil solution, it is challenging to empirically track and verify pedogenic $CaCO_3$ precipitation *in-situ*.

The present guidelines only consider CO_2 drawdown to occur in time and space where non-water limited, and non-saturated soil moisture regimes tend to prevail (see Chapter 3.1.2 on decadal aridity index). Precipitation of persistent pedogenic $CaCO_3$ is unlikely under such moisture regimes, as in regions with sufficient precipitation a supersaturation of the soil solution is less likely. Further, if $CaCO_3$precipitation occurs in the topsoil, due to temporary drought or evaporation of irrigation water, its consecutive redissolution in the rhizosphere is likely. At circumneutral pH, the dissolution rate of calcite is 5-6 orders of magnitude faster, than those eligible silicate rocks. (Arvidson et al, 2003).

The present method is deploying a 10% safety margin to the gross C-Sink potential at field level, to cover the possible precipitation of persistent, paedogenic calcium carbonate (M_{soil} = 0.9). As per the reactions stichometry 10% margin taken form the C-Sink is equivalent to cover the permanent loss of 20% bicarbonate from the soil solution and its conversion into calcium carbonate.

4.2 Losses in groundwater and rivers

Groundwater bodies are dominated by circumneutral pH values, at which bicarbonate is the dominant DIC species and relevant $CaCO_3$ precipitation and CO_2 outgassing is not expected due to sealing.

In a central European context (example Germany) about 7% of the permanent groundwater-bodies are sourced annually (BMU, 2008; BGR, 2016), most of which is sourced from below forest areas, not from below agricultural lands.

If redirected towards domestic or industrial use the groundwater likely reaches riverine systems faster, than during the natural hydrological cycle.

Groundwater redirected for agricultural irrigation purposes with consecutive partial evaporation can be conceived as a scenario possibly leading to carbonate precipitation, yet redissolution in agricultural systems is likely.

Rivers in Europe typically show a pH of approximately 8 (Example: Rhine River, Germany) Dissolved CO2* represents a share of <1% of the DIC, while bicarbonate is the dominating species. Thus, relevant carbon loss due to outgassing is unlikely. Losses of DIC and CO_2 exchange in river systems are subject to ongoing research – the present sub-chapter is expected to be updated soon. This is of relevance to better describe riverine systems outside of central Europe (e.g., tropics, or Scandinavia), which show a distinct water chemistry. At present, substantial losses from groundwater and riverine systems are not expected ($\mathbf{M}_{aquatic}$ = 1).

4.3 The ocean

If the DIC is reaching the ocean (time horizon depending on proximity of rock powder application site to river systems), the contribution of introduced DIC to oceanic carbon storage is determined by environmental parameters like ocean temperature, salinity, and partial pressure of CO_2 (Hartmann et al. 2013).

Dissolved inorganic carbon in the ocean is attributed a mean residence time of several 1,000-10,000+ years (Rau et al. 2011; Renforth and Henderson, 2017). A share of approximately 10% will be present as carbonate (CO_3^{2-}). Partly, CO_3^{2-} will be utilized by marine biota for shell formation through calcification (i.e., the biotic formation of solid $CaCO_3$). The precipitation of oceanic $CaCO_3$ is almost exclusively facilitated by marine biota (Renforth and Henderson, 2017). While some of the calcified DIC will ultimately end up as particulate inorganic carbon in the ocean's sediments (geological storage), the process of biogenic calcification can be a net CO_2 source (Morris and Humphreys, 2018). It is unlikely, that the complete pool of introduced CO_3^{2-} will be subject to biogenic calcification on time scales relevant for climate action, mitigating anthropogenic climate change. Lastly, the share of dissolved CO_2* at typical ocean pH can be neglected.

Considering contemporary mean surface ocean conditions of 17°C, a salinity of 35 and a conservative pCO_2 estimate of 600 µatm (representing RCP 8.5 in 2050), a share of 86% of the introduced DIC will be preserved, while 14% is released to the atmosphere (Renforth and Henderson, 2017; Lewis et al., 2021). Thus, any CDR resulting from successful in field weathering must be multiplied with a factor of 0.86 to account for the midterm CDR efficiency, as lastly determined by the oceanic carbonate equilibrium. (M_{marine} = 0.86)

5 Carbon expenditures

For the effectiveness of any C-Sink as a tool in mitigating climate change, it's essential that the net C-Sink is quantified, certified, and recorded in the Swiss Carbon Registry. The emissions generated in the creation of a C-Sink are termed as "Carbon Expenditures". All such carbon expenditures must be meticulously documented for each project activity, as detailed in Chapter 2. These carbon expenditures are then registered as the project's emission portfolio within the Swiss Carbon Registry. For every certification standard falling under the Global C-Sink umbrella, a distinct offset of the emission portfolio - encompassing all the recorded carbon expenditures - is mandated prior to a C-Sink's inclusion in the Swiss Carbon Registry. Therefore, every certified and recorded C-Sink signifies a **net removal of CO_2** from the atmosphere.

The rock powder value chain is requiring substantial energy inputs from mine to field, which is causing direct and indirect greenhouse gas emissions in the form of CO_2. Operations emitting more - or only slightly less -CO_2 than they are sequestering, e.g., due to long transport, are rendered uneconomic due to the costs of C-Sink retirement for compensation and fail to enter the carbon market.

Carbon expenditures are calculated as follows:

Equation (5):

$$Carbon\ expenditures = Ex_{production} + Ex_{transport} + Ex_{application}$$

$\boldsymbol{CE}$ = *Carbon expenditures t CO_2e t^{-1} rock powder applied.*
$Ex_{production}$ = *Emission factor for rock powder production in t CO_2e t^{-1} rock powder.*
$Ex_{transport}$= *Emission factor for transport emissions in t CO_2 t^{-1} rock powder*
$Ex_{application}$= *Emission factor for application emissions in t CO_2 t^{-1} rock powder*

The calculation of the emission factors is described in the following subchapters.

5.1 Emissions from mining

As per the current version of the guidelines, standard values from peer-reviewed literature are used to estimate $Ex_{production}$, the carbon expenditures associated with the production of 1 t of rock powder. As per Table 5 below.

Table 5: Lump-sum emission factors for rock powder production

Operation	Emission factor	Unit	Source
Mining	0.007	tCO2 t rock^{-1}	Rinder and Hagke (2021); Moosdorf et al. (2014)
Comminution (valid for <100µm)	0.02	tCO2 t rock^{-1}	Strefler et al. (2018); Rinder and Hagke (2021);
Sum ($Ex_{production}$)	**0.027**	**tCO2 t rock^{-1}**	

If it can be plausibly declared to the certifier, that the employed rock powder is a by-product, e.g. originates exclusively from a storage of mine tailings or unintentionally produced fines:

$Ex_{production} = 0$

Only after full implementation of the certification framework, i.e., after the accreditation of a MRV technology for the quantification of ERW based CDR, the scope of chapter 5 will be increased. Thereafter, constituting individual audition and certification of the mining facilities obtaining project specific values for $Ex_{production}$ according to chapter 5.1.1-5.1.3.

5.1.1 Emission factors for mining operations

To calculate the carbon expenditures originating from scope 1 and scope 2[4] emissions the following factors need to be quantified:

1. E_{mining}: Mean electrical energy consumption for mining operations in MWh electricity used per 1 t rock mined. If additional thermal energy is required (e.g., steam production) the associated energy requirements need to be indicated separate.
2. $E_{milling}$: Mean electrical energy consumption for comminution operations in MWh electricity used per 1 t rock broken down to the required particle size distribution of the product. If additional thermal energy is used (e.g., steam production) the associated energy requirements need to be indicated in separate.

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[4] According to established *greenhouse gas protocol (GHG Protocol, 2022)*, a company's emissions are classified in three different categories, i.e., scopes (scope 1-3). Scope 1 covers direct emissions by the company (e.g., fuel use), scope 2 covers indirect emissions from production of procured energy (electricity, steam, heat, cooling). Scope 3 covers further indirect and often diffuse emissions, as, e.g., upstream emissions (emissions from suppliers/ premanufacturing) or commuting employees. The reporting of scope 1 and 2 emissions is mandatory for many companies, while scope 3 emissions are voluntary, because they are difficult to monitor.

3. $F_{Mining+Milling}$: Mean fuel consumption for mining and comminution operations in L diesel used per 1 t rock mined and milled.

Scope 3 emissions are included by a safety margin of 10%. Thus, the carbon expenditures are calculated according to equation **(6)** as follows:

Equation (6):

$$Ex_{production} = \left((E_{mining} + E_{milling}) * EF + (F_{mining} + F_{milling}) * 0.0032\ t\ CO_2e \right) * 1.1$$

$Ex_{production}$ = *emission factor in t* CO_2e t^{-1} *rock powder.*
E = energy usage in MWh t $rock^{-1}$
EF = *national emission factor for the electricity generation in t* CO_2e MWh^{-1}.
F = *fuels (diesel) usage in L*
0.0032 t CO_2e = *mean* CO_2e *emission from burning 1 L diesel (Juhrich, 2016)*
1.1 = *margin to incorporate scope 3 emissions.*

5.1.2 Attribution of emissions in multi-product operations

Especially for the first decade of ERW, we expect that there will be only few mines that exclusively produce rock powder for ERW. Instead, rock powder can be

- Fines, i.e., by-product from sieving agglomerates for construction purpose
- Fines / "saw dust", i.e., by-product from cutting stone.
- Mine tailings, i.e., by-product of mining ores or other geogenic resources
- A co-product of agglomerate production

By-products that previously had no use can be considered a climate neutral product, as they are created unintentionally. Thus, all emissions are attributed to the main product. However, looking at the potential scale and expected economics of ERW, it is likely that such by-products may become a valuable co-product that contributes to the overall profitability of the mining operation.

For a transition period of 3 years past the initial certification, a mining company has the option to plausibly declare to the certifier, that the sold rock powder originates exclusively from a storage of mine tailings or unintentional by-products such as fines. If this is made plausible:

$Ex_{production} = 0$

Past this transition period, mine tailings and fines must additionally be attributed with a share of the scope 1 – scope 3. The share of attributable emissions is equivalent to the share of revenue[5] generated from rock powder sale, from the total annual revenue generated from the

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[5] Based on aggregated economic data from the calendar year, prior to certification. The applicable share of scope 1 and scope 2 emissions to be attributed must be updated annually. This procedure may cause an under

mining activities. (e.g., if 5% of the revenue is generated from sale of rock powder, 5% of the company's scope 1 – scope 3 emissions must be attributed to the rock powder production).

Downstream carbon expenditures from material transport past factory gate and field application must be quantified through a tracking system accredited by Carbon Standards.

5.2. Emissions of rock powder transport

The factor $Ex_{transport}$ must be calculated based on transport distance according to equation **(7).**

Equation (7):

$$Ex_{transport} \quad = distance * 0.000111\ t\ CO_2e\ km^{-1}$$

$Ex_{transport}$= *Transport emissions in t CO_2 t^{-1} rock powder*
distance = *transport distance in km (factory gate to field)*
0.000111 t CO_2e = *mean CO_2e emissions from transporting 1 t km^{-1} (UBA, 2022)*

The emission factor is sufficiently conservative to also cover the empty run of a truck returning to the factory gate. Such empty-runs are typical within the transport logistics of bulk goods. If the delivery can be partially achieved by train and / or ship, correspondingly low emissions can be accounted for at the justified request of the C-Sink Manager. The same applies to the use of electric vehicles or other climate-friendly innovation.

5.3. Emissions of rock powder application

For the field application a conservative estimate of 0.004 t CO_2 per ton rock powder (Moosdorf et al., 2014) applies. If significantly lower emissions for land application (min. 25% reduction; max. 75% reduction) can be demonstrated to the certifier, this emission factor can be adjusted upon request.

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estimation in phases of exponential growth, however, remains appropriate and pragmatic in the early stages of the ERW industry.

6 Environmental factors influence rock weathering

In the field, weathering rates are influenced by a complex array of environmental factors. An integral part of the present certification is that weathering is basically possible to a relevant extent based on sufficient precipitation and the resulting soil moisture.

To prove and to calculate actual CDR resulting from a Rock C-Sink, at least the following factors should be considered, explicitly or implicitly, if ex-ante modeling of CDR is pursued:

- Soil temperature
- Soil moisture
- Soil pH
- Soil / Rhizosphere CO_2 concentration
- Biogenic weathering agents, largely determined by the type of vegetation

In this context, "explicitly" can mean that this factor must be entered into the model as a site-specific variable. However, one or more (if not all) factors can also be considered "implicitly" by including data e.g., from a reference measuring station or a reference lysimeter exposed to sufficiently similar soil, climate/weather[6], and management. This can be achieved by field stations / field trials in sufficiently short distance or by simulation under controlled conditions in growth chambers or greenhouses.

To enable the identification of relevant agroclimatic data, as required by a modelling approach to be accredited the registration of the exact spatial coverage of the field must be documented. Such data will allow for the identification and use of reference data e.g., climatic data, sample collection or in-field measurements for model parameterization.

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[6] The climate is the average of the dynamic processes in the earth's atmosphere, i.e., the weather at a defined space. In the world of climate change, relevant aspects such as rainfall are changing rapidly. Thus, a lysimeter exposed artificially to the average of e.g., 1990-2020 climatic conditions might not provide relevant results for the weathering of the three previous years, when the location was subject to e.g., intense drought. Nonetheless, greenhouse (pseudo-)lysimeter approaches are important, but C-Sink Manager need to reason carefully, how they translate the results to the field in the light of climate and actual weather. Again, longer periods are less prone to error.

7 Measuring or modelling CDR: Method admission

The present guidelines provide for the calculation and documentation of the CDR_{max} and the calculation of the net C-Sink potential of an ERW project using generic safety factors.

Actual weathering and actual creation of a C-Sink (DIC storage) can be calculated according to external methods, that must be accredited by Carbon Standards upon request. Such methods can be open access or proprietary, can be owned by a C-Sink Manager or a third party as a for-profit or not-for-profit service provider.

Accredited methods will be listed on the Global C-Sink webpage (link) and in the latest version of the Global Rock C-Sink guidelines. As of December 2023, no accredited method is available.

Methods may measure on the actual weathering/ CDR (in real time or ex-post at discrete points in time), but models may also include the downstream fate of the bicarbonate, with the goal to reduce uncertainty, by replacing the generic safety factors to convert CDR_{max} into the Rock C-Sink potential, by individual project cases.

Approaches are mentioned here that could lead to an accredited method in the short to medium term. This list makes no claim to completeness and has no influence on the accreditation process for a specific method.

Empirical quantification of in field weathering: Qualified measurement approaches to determine in-field weathering rates, based on empirical measurements, conducted on site. To be qualified, a method must reliably and reproducibly quantify the products of successful weathering reactions. Weathering products (total alkalinity, additional bicarbonate) that correlate to successful CDR. It is not sufficient to quantify the reduction of rock powder in the field, as rock powder can also be lost due to erosion or leaching. Experimental approaches may sample the liquid phase (e.g., lysimeter trials analyzing soil leachates, cation-exchange resins, or soil extractions), the solid phase (e.g., analyzing soil magnesium to titanium ratios), or gaseous phase (e.g., monitoring soil CO_2 concentrations). Continuous measurements in each single field (and ex-post certification and credit issuance) are likely cost-prohibitive or easy to manipulate.

Measurements in qualified reference experiments: Empirical measurements must not be conducted in every field. The present guideline allows for the construction of representative reference experiments, approximating relevant agro-climatic conditions (similar soil type, similar soil management, similar climate temperature/precipitation). Empirical measurements of weathering products can be applied to such reference field- or mesocosm experiments and results applied for multiple ERW projects situated in comparable agro-climatic conditions.

Further, the present guideline allows for the extrapolation of weathering curves based on ≥3 years of data form qualified reference experiments.

Calculation through validated, process-based models: Another option for the quantification of time dependent weathering is the employment of process-based/ reactive transport models. If modeling approaches are employed the model must consider rock characteristics (mineralogy, elemental composition, particle size distribution and specific surface area), same as relevant agro-climatic conditions to enable site specific model runs. Any process-based model should be validated against ≥3 years of data form qualified reference experiments to prove and ensure sufficient accuracy (±10%) in predictive power. Modeling approaches may resemble process-based models such as "Soil Cycles of Elements simulator for Predicting Terrestrial regulation of greenhouse gases: **SCEPTER** v.0.9" by Kanzaki et al. (2022) or models developed by Chipolla et al. (2021a, 2021b, 2022), and Beerling et al. (2020), reactive transport models, e.g. implemented in **PhreeqC** as e.g., in Kelland et al. (2020), ensemble models based on model intercomparisons (**Rock Chip Project**, Beerling et. al., *in preparation*) or extrapolations from reference experiments.

Note, that any certification framework under the Global C-Sink umbrella only certifies actual CDR (ex-post, after carbon removal took place), thus even if modelling approaches enable extrapolations in the future, CDR will not be carried ex-ante. Only the actual CDR that occurred until present day can be certified. Ther certified amount may be updated annually.

Requests for method accreditation must be addressed to Carbon Standards. Applicants are encouraged to contact Carbon Standards in advance, especially if the request will contain confidential information. The requests should follow the suggested structure:

1. Cover letter
   Please provide some background on your organization, your motivation to submit the request and how the method will be used (open access, proprietary for own projects, service provider etc.). If applicable, describe which parts of the method are confidential. Discloser agreements with Carbon Standards *can be formulated.*
2. Description of the method (high level)
   Please describe the overall approach and principles of your method. Unlike section 6 and 7, this part may not be classified at confidential and must address a general professional audience, i.e., no specific scientific background is needed to understand this, beyond the fundamentals described in the Rock C-Sink guidelines. Only include the most important references.
3. Scope
   Please describe the projects to which the methods shall be applied (validity range), e.g., with reference to climate, geographic scope, type of rock power application and land management (incorporated, under mulch, in irrigated systems, etc.).
   Please define if the method addresses weathering rates only or also downstream effects (DIC transport, losses and storage).
4. Internal quality control, validation and peer-review
   Please describe how you ensure that the results or your methods are valid. When models are used, describe how they were validated. In an ideal case, the method was already published by the applicants or their scientific supporters in a scientific journal with peer-review. Here, we encourage to submit the reviewer comments received during the publication process to ease the evaluation. In other cases, describe how your method is backed by literature. Please describe how your method / your team is supported and reviewed by independent experts.
5. Revision and updating
   How do you plan to update your methods, e.g. include new scientific data into models or how your experiments to conduct measurements will continue.
6. Detailed description of the method
   In the case of proprietary methods, this section (or parts of it) may be confidential.
7. Annexes
   Optional, usually not included in the published version, may include confidential information and e.g. reviewer comments from scientific publication, validation reports and / or the scientific publication of the applicants or their scientific supporters if the publication is not open-access.

Requests will be evaluated by a team of experts with backgrounds in certification, geo- and environmental science, and IT. Thus, except for the detailed description, the text must address a general audience. The detailed description should be considered a scientific text.

Upon admission, the request will be publicly available on the Global C-Sink webpage, except for the Cover Letter and sections highlighted as confidential.

Accreditation may be subject to conditions regarding the use of data, obligations to publish certain data, and a period for re-evaluation. In the future, Carbon Standards aims at intercomparison of methods, e.g., by some kind of ring-trials. However, this will only be outlined and planned once enough methods passed the first accreditation.

Following principles of revision and refinement, accredited methods must be upgraded or replaced, once new empirical findings, or comprehensive process-based models become available **and** validated. Thus, constantly adapting to the state of science.

8 Retention samples of rock powder and soil

Projects creating certified C-Sinks may be established before a method to calculate actual CDR as per chapter 7 is in place that is applicable to the specific project and site. Still, projects must ensure that potentially relevant data will be available for future to quantify actual CDR. The following factors may be considered explicitly or implicitly when calculating actual CDR. This may include both rock powder and soil properties, such as:

- mineralogy, elemental composition, particle size distribution and specific surface area of the rock powder
- particle size distribution, cation exchange capacity, cation content, (organic) carbon content and pH of the soil

However, since it is not yet clear today which of this data must be available and in what form or quality, it is inappropriate to mandate an all-encompassing analysis today. It would also be too great a financial burden on the projects. Instead, representative samples of both soil and rock flour must be taken and stored. Storage is the responsibility of the C-Sink Manager.

Use of commercially available tamper evident sample bags with unique IDs allows these samples to be clearly and incorruptibly attributed to the project even years later. The IDs of the samples is registered in the project documentation.

Representative soil samples should be drawn immediately before rock powder application by the farmer, C-Sink Manager, or a contractor. Soil samples must be air dried and packed immediately after drying. A soil sampling protocol is provided in the Annex 10.1.2.

Representative rock powder samples should be sampled before rock powder application by the farmer, project manager or a contractor. A rock sampling protocol is provided in the Annex 10.1.1. If several rock powder applications are carried out within a short period of time (max. 1-2 months) with material from the same source, one sample ID can also be registered in the project documentation.

9 Certification

9.1 Rock powder supplier and product certification

The certification of the mining company and rock powder product is carried out by the accredited certification body. During an on-site visit, all requirements and data regarding environmental protection, work safety, process emissions and rock powder sampling are controlled.

To collect and verify the data specified in the following subchapters, an on-site inspection has to be conducted annually.

9.1.1 Basic requirements for the supplying company

9.1.1.1 Environmental Protection

The mining and comminution operation supplying the rock powder must be an official company registered and licenced according to national regulations.

The complete operation from land development, to mining, milling, delivery of rock powder and storage of mine tailings must adhere to all national regulations on environmental protection. This includes regulations on process emissions, particulate matter, soil- and water protection and prohibited substances.

Any operation suspected to cause intrusion into protected areas or expropriation of traditional land rights or private properties of third parties cannot be covered under the present guidelines.

9.1.1.2 Health and work safety

Fire and dust protection regulations must comply with local and national regulations throughout the entire production, transportation, and user chain.

All workers must be informed in writing about possible risks and dangers of and around the production facility and sign the document. This concerns the dust and respiratory protection.

All staff engaging in production and transport of rock powder need to be equipped with suitable personal protection equipment. For the operation of material mills this includes an appropriate respiratory protection.

9.1.2 Emissions of rock powder production

During on-site inspection, the rock powder producer must provide information on the electricity and fuel consumption using respective invoices and the company's balance sheet or other evidence that all energy consumption has been disclosed.

As carbon expenditures are calculated per t rock powder and the attribution of carbon expenditures also depends on the contribution of the rock powder for ERW to the total revenue of the company, respective data and the company's balance sheet need to be disclosed.

The data of the past year will be used for rock powder batches of the subsequent year.

Further, the geolocation of the production facility needs to be documented, to calculate transport distances from factory gate to application site.

9.1.3 Routine analysis and definition of batches

A rock powder production batch is defined as a documented amount of rock powder, produced under the same production conditions (technology and energy input), being mined from a single geological formation, or removed from a mine tailings stock of defined mineralogical and elemental composition.

A routine analysis of the rock powder characteristics must be caried out at least every six months and after a change in deployed mining and/ or milling technologies. Thus, one year's production will be assigned to at least two production batches.

A routine analysis of a rock powder batch must cover all parameters as listed in Annex 10.1.1. Upon publication of a list of laboratories accredited for Rock C-Sink analysis by Carbon Standards, only data from those laboratories will be accepted. The accredited laboratories will be listed on the website of Carbon Standards.

For analytical purposes, representative composite rock powder samples of >10 kg must be drawn from the mine tailings stock storage (discharge side) – or sampled from ongoing production following the sampling protocol in Annex 10.1.1.

Each production batch is assigned a unique batch ID.

9.1.4 Delivery unit ID

Before a delivery can happen, the batches must be certified. Each ton of rock powder ordered and applied by a farmer or other C-Sink Manager must be associated to a unique delivery-unit ID.

All delivery-unit IDs must be associated to a certified batch ID (see chapter 9.1.3 above). Delivery unit IDs are associated to the ongoing production batch (6 month interval). Only after the routine analysis caried out successfully (marking start of the next batch) the delivery units are assigned to the next batch.

The delivery unit IDs and associated rock powder quantities must be accessible for the certification body. The delivery unit ID can be identical to the reference number printed on the delivery note as generated by an inventory management or enterprise resource planning software to allow easy and seamless integration into established processes.

The delivery note issued by the mining company or distributor must indicate the batch ID and delivery-unit ID in plain text and QR code. The QR code is further linking to a viewable online database where the rock characterisation according to Annex 10.1.1 can be reviewed by the C-Sink Manager or farmer.

9.2 Pilot projects: Use of non-certified rock powder

Rock powder from a non-certified source may be used on a one-time basis for pilot projects where up to 2000 tons of rock meal is applied over a 12-month period. The C-Sink Manager must register the location of the mine for the calculation of the emissions of rock powder transport. For production-related emissions literature values are applied (cf. chapter 5.1).

Upon well-reasoned request, Carbon Standards may issue a written exemption that such application may be repeated in the following year. Thereafter, the source of the rock meal must be certified.

9.3 Certification of rock powder application

For successful certification of a Rock C-Sink potential, a part of a certified Rock powder batch must be applied to an eligible land unit and all required data and supplementary files must be compiled in the provided online tools and approved by the certification body.

The C-Sink Manager must provide farm and field specific data to the online tools which includes:

- Landowner name and address
- Field size
- Field GPS-coordinates (Point coordinate of the (approximated) centre of the field and a KML polygon depicting the total area of the field)
- Date of application
- Date of soil incorporation (where applicable)
- Application amount (t rock field^{-1})

- Delivery unit and Batch-ID
- Land eligibility statement
- Soil characterization or ID of soil retention sample
- Rock characterisation or ID of rock powder retention sample

This data is supported by uploading the following files:

- Delivery notes of the rock powder.
- Geo-tagged picture of delivered rock powder.
- Geo-tagged picture of rock powder application.

A field is defined as connected land unit being subject to identical land management and having a maximum size of 30 hectare. Closely adjacent land units (<50m distance, e.g. separated by dirt roads, hedge rows or streams) may also be consolidated as one field in the context of project documentation and soil analysis – as long soils show largely uniform characteristics (same soil type sandy/loamy/clayey and max 0.3 units pH difference).

All data entered by a C-Sink Manager must be verified by the certification body. Upon completion and verification of data input the field specific C-Sink potential will be calculated and issued automatically.

9.3.1 Geographic validity range

The geographical range of the present certification guideline is global.

Specific country annexes may be added to the guideline to integrate with, or acknowledge, relevant national regulations on rock powder application to croplands.

9.4 Self-documentation of rock powder application

As long as a full certification based on the present guidelines is not yet offered, it is possible to self-document rock powder applications in such a way that the data thus conserved can be used for later certification. The procedure is as follows:

Data collection

All required data is collected and documented using the provided spreadsheet template.

Soil samples are taken and stored in sealed tamper-proof bags after drying. The same applies to the rock powder employed. The respective IDs are recorded in the above-mentioned table.

The Spreadsheet will be complemented by a collection of relevant documents (delivery notes, georeferenced photos, *.klm files of plots, analysis reports where applicable).

Data upload

The overall data package is uploaded to Zenodo (https://zenodo.org) or any other independent general-purpose open repository that generates unique IDs for data (for Zenodo: DOI of each uploaded file) and clearly documents the upload date so that later modification is not possible.

Verification of self-documentation

The Ithaka Institute offers a plausibility and completeness check of the data. The C-Sink Manager submits the DOI of the data. Ithaka reviews it and clarifies any questions with the C-Sink Manager via video conference.

Ithaka creates a document that confirms the successful audit and states which data IDs (usually DOI) have to be assigned to the project. C-sink Potentials of projects documented this way, can retroactively be converted in to C-sinks with accredited monitoring methods.

10 Additionality

The application of small amounts of rock powder (< 2t ha^{-1}) constitutes a traditional agricultural practice to replenish essential micronutrients in the soil. In modern day agriculture large scale rock powder applications, as for soil pH adjustments (liming) or provision of macronutrients is neither typical nor economically feasible, comparing costs with anticipated short-term agronomic gains.

Large scale rock powder applications are not part of common farming practice an only become feasible as per the additional revenue stream generated from C-Sink potentials. Any rock powder application exceeding 2t ha^{-1} generating a climate service and long-term agroecological benefits, represents an additional C-Sinks.

Any C-Sink is providing a climate service, independent of its cause of creation (regulatory surplus, financial additionality, ecological additionality etc.). A C-Sink certification serves to add urgently needed value to any ERW-based solution and its agro-ecosystem services.

11 Valorisation

The certified Rock C-Sink potential is a measure for the size a Rock C-Sink will eventually reach. It is decoupled from the temporal evolution of the actual C-Sink. Thus, the Rock C-Sink Potential must not be sold as a compensation for CO_2 emissions. Rock C-Sink potentials may only be traded among registered C-Sink Managers/ clients.

Once, actual CDR

a) was achieved over time by weathering,
b) its extend was calculated/measured according to an accredited method, and
c) the entry in the Swiss Carbon Registry was updated accordingly,

The respective Rock C-Sink may be valorised and retired as a compensation for an emission of fossil CO_2 or used as any other type of climate service.

11.1 Accreditation of C-Sink traders

A C-Sink trader is an entity coordinating and managing the trade of certified and registered C-Sinks or C-Sink Potentials being part of C-Sink portfolios.

To be eligible under the present guidelines a C-Sink trader must be accredited by Carbon Standards.

C-Sink traders may also engage in the provision of tracking systems, covering the transport and downstream carbon expenditures (past factory gate emissions), given suitable infrastructure is present. The respective tracking systems must be approved by Carbon Standards.

Glossary

C-Sink	A carbon sink is the result of (1) carbon dioxide removal (CDR) from the atmosphere, (2) the transformation of the CO_2 into a storable form and (3) storage of the carbon for verifiably duration in a non-atmospheric carbon pool. Depending on the duration of storage, a C-Sink may be described as short term <100 years or long term > 100 years.
100% 1000 years principle	To compensate the emission of CO_2 with C-Sinks, an equivalent amount of CO_2 (= 100%) must be removed from the atmosphere and stored for at least 1000 years. This requires instant removal of the total amount of carbon and ensuring uninterrupted, i.e., constant storage for 100 years.
Carbon expenditures/ Emission portfolio	Carbon expenditures represent the greenhouse gas emissions associated with the establishment and maintenance of a C-Sink, essentially reflecting the carbon footprint of the C-Sink itself. These expenditures are tracked and reported on a monthly basis, using the CO2e metric. The carbon expenditures of a project are aggregated in the project's emission portfolio. The emission portfolio of any project must be offset before any carbon sink can be registered.
C-Sink Retirement	Using a certified C-Sink to compensate the global warming effect of greenhouse gas emissions retires the C-Sink certificate, which then cannot be used for other compensations or the declaration of climate effective action anymore. The retired C-Sink certificate is no longer available for sale or resale. Still, the retired C-Sink remains part of the registry.
Swiss Carbon Registry	The Swiss Carbon Registry is an independent, secure, digital database that records certified C-Sinks along with their corresponding C-Sink curves. This registry serves as a library for compiling C-Sink portfolios. Furthermore, it provides essential information on each C-Sink, such as its current status (e.g., whether it's available for sale or has been retired), the date of its CO2-removal, the establishment date of the C-Sink, and its geographical location. Such sector-specific, global or national C-Sink registers offer a comprehensive overview on contributions to Carbon Dioxide Removal (CDR).
C-Sink Trader	A C-Sink trader is an entity coordinating and managing the trade and registration of carbon sinks and may create carbon sink portfolios. To be eligible under the present guidelines a C-Sink trader must be accredited by Carbon Standards International.
Mine tailings	Unintentionally produced rock powder, originating as a by-product from other mining operations which already took place in the past or are part of a business-as-usual mining operation.
C-Sink Manager	The C-Sink Manager refers to the party organizing and facilitating an enhanced weathering project and applying for its certification under the present guidelines. The C-Sink Manager can be a real person e.g., a landowner or farmer or legal person e.g., a company aggregating and

	coordinating farmers. The C-Sink Manager must provide all data requested by the certifier.
Rock C-Sink	A generic term, coined to describe C-Sinks generated through enhanced weathering of rocks, implying a consecutive carbon storage in mineral, or dissolved inorganic form.
Rock C-Sink Potential	A carbon sink potential in enhanced rock weathering refers to the conservatively calculated carbon sink (= carbon dioxide removal + long-term storage) that will be built-up on the long-term. A Rock C-Sink potential can be given as t CO_2e per field or project.
Theoretical Carbon Dioxide Removal Capacity (CDR_{max})	The theoretical carbon dioxide removal capacity (CDR_{max}) is equal to the amount of carbon sequestered by a given rock after complete weathering. The theoretical carbon dioxide removal capacity is calculated based on the elemental composition of a rock and a safety factor of 0.9 to account for the formation secondary minerals that reduces the release of metals and thus alkalinity. It is given as the mass ratio of CO_2 transformed into bicarbonate to initial rock dry weight in t CO_2 t $rock^{-1}$. For examples, a CDR_{max} of 0.418 t CO_2e t^{-1} indicates that 1 t rock can sequester a maximum of 0.418 t CO_2 when 100% weathering is achieved.

Abbreviations

Ai	Aridity index
C	Carbon
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
C-Sink	Carbon sink
CDR	Carbon dioxide removal
CDR_{max}	Theoretical carbon dioxide removal capacity
DIC	Dissolved Inorganic Carbon ($[CO_2] + [HCO_3]^- + [CO_3]^{2-}$)
ERW	Enhanced rock weathering

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10 Annex

10.1 Analytical methods

10.1.1 Rock powder analysis:

In preparation

Rock powder sampling protocol: To obtain a representative rock powder, a batch (defined as 6 month of production) must be sampled within the first month of production according to the following exact methodology.

A. Rock powder from continuous production

1. On three consecutive days, 8 samples of 3 liters each are taken at intervals of at least one hour directly at the discharge of the freshly produced material. This sampling can also be done by an appropriately adjusted automated cross-stream sampler.

2. The 24 subsamples are combined and homogenized, to form a composite sample.

3. The taking of each of the 24 samples (= 3 x 8 daily samples) as well as the homogenization and sample division (see C) must be documented with the exact sampling times in a sampling protocol.

B. Rock powder from mine tailings storage

1. At 24 different spots of the depots discharge side, samples of 3 liters each are taken.

2. The 24 subsamples are combined and homogenized to form a composite sample.

3. The taking of each of the 24 samples (= 3 x 8 daily samples) as well as the homogenization (see C) must be documented with the exact sampling times in a sampling protocol.

C. Homogenizing and dividing of the sample.

1. The 72-l composite sample is thoroughly mixed by 3-fold translocation of the rock powder by shoveling three times from one pile to another.

2 A sub-sample of 1,5 l is then taken at 15 spots in the mixed pile.

3. The 15 subsamples are again poured together.

4. The new 22,5 l subsample has than to be homogenized thoroughly by 3-fold translocation of the rock powder by shoveling three times from one pile to another.

5. From the mixed pile of the 22,5 l subsample, 15 subsamples of 150 ml each shall now be taken at 15 different spots in the pile and united.

The sample is to be sent to the accredited laboratory for analysis or stored in a sealed bag as a retention sample for later analysis.

Moisture content at factory gate

X-ray fluorescence analysis:

Bulk mineralogical analysis by X-ray diffraction

Particle size distribution

Nitrogen (N)

Phosphate (as P2O5)

Potassium (as K2O)

Magnesium (Mg)

Sulfur (S)

Boron (B)

Copper (Cu)

Zink (Zi)

Cobalt (Co)

Alkaline Components (as CaO)

Selenium (Se)

Chlorin (Cl)

Arsenic (As)

Lead (Pb)

Cadmium (Cd)

Total Chromium (Cr)

Nickel (Ni)

Mercury (Hg)

Thallium (Tl)

Rock density

10.1.2 Soil analysis

In preparation

Soil sampling protocol:

Soil samples for mandatory analysis (soil pH and trace metal concentrations), same as soil retention samples must be drawn before a rock powder application takes place.

Individual soil cores must be drawn with a boring rod, penetrating the top 30 cm of the topsoil.

Sampling locations must be randomly scattered over the whole target area.

The individual soil cores must be mixed thoroughly, until presenting one homogeneous one composite sample.

The composite sample must be first air dried and then stored in a sealed sample bag presenting a unique ID/ reference to the C-Sink Manager, field and sampling date.

The sealed bags can be shipped for analysis purpose or stored as a retention sample by the C-Sink Manager.

Table A1: Sampling resolution:

Field Size	Minimal sampling density
≤1 ha	10 cores ha^{-1}
1.1- 5.0 ha	5 cores ha^{-1}
5.1-10 ha	3 cores ha^{-1}
10.1-30 ha	1 cores ha^{-1}

The composite sample must comprise at least 1kg soil dry weight.

Soil Ph

Cadmium,

Lead

Chromium

Copper

Nickel

Zinc

Mercury

10.2 Legal aspects

10.2.1 Rock powder application under German law

As per its mean composition (relatively low nutritional content), rock powders do not qualify as inorganic single or multi-nutrient fertilizers.

Natural rock powders, not including mineral waste streams or artificial silicates, are approved soil amendments in the form of soil conditioners as per the German Federal Fertilizer Regulation, DüMV 2012 §4 (3) 2. Rock powders are also approved by organic certification schemes as *bioland* or *demeter.*

For a rock powder to be admissible as a soil amendment under German law, the following limit values must be respects. Further, constituents must be indicated on the product label/ in the product description if the respective labeling threshold is exceeded.

Table A2: Label and limit values for soil conditioners under German law

Parameter	Labelling Threshold	Labelling Threshold Tolerance	Limit Value
Nitrogen (N)	0.1%	50%; 1%-Point	*non*
Phosphate (asP_2O5)	0.1%	50%; 1%-Point	*non*
Potassium (asK_2O)	0.1%	50%; 1%-Point	*non*
Magnesium (Mg)	0.1%	50%; 1%-Point	*non*
Sulphur (S)	0.1%	50%; 1%-Point	*non*
Boron (B)	0.01%	20%; 0.4%-Point	*non*
Copper (Cu)	0.05%	20%; 0.4%-Point	*non*
Zink (Zi)	0.1%	20%; 0.4%-Point	*non*
Cobalt (Co)	0.004%	20%; 0.4%-Point	*non*
Alkaline Components (as CaO)	5%	50%; 2.5%-Point	*non*
Selenium (Se)	0.0005%	25%	*non*
Chlorid (Cl)	*any value*	0.2%	*non*
pH	*any value*	0.4 units	*non*
Arsenic (As)	20 mg kg^{-1}	50%	**40** mg kg^{-1}
Lead (Pb)	100 mg kg^{-1}	50%	**150** mg kg^{-1}
Cadmium (Cd)	1 mg kg^{-1}	50%	**1.5** mg kg^{-1}
Total Chromium (Cr)	300 mg kg^{-1}	50%	*non*
Chromium (Cr^{VI})	1.2 mg kg^{-1}	50%	**2** mg kg^{-1}
Nickel (Ni)	40 mg kg^{-1}	50%	**120** mg kg^{-1}
Mercury (Hg)	0.5 mg kg^{-1}	50%	**1** mg kg^{-1}
Thallium (Tl)	0.5 mg kg^{-1}	50%	**1** mg kg^{-1}

Further, the baseline concentration of trace elements in the soil must not be exceeded, to adhere to the precaution values of the German Federal Soil Protection Act (BBodSchv, 2020 Annex 2.4). If this precaution values are exceeded, German law only allows for limited application of substances containing further loads of the respective trace elements. However, the present guidelines do not allow **any** further rock application if the precaution values are exceeded.

Regulations of the federal fertilizer regulation (DüV, 2017) must be respected. Relevant nutrient loads contained in the rock powder must be documented in the farm nutrient budget.

The P_2O_5 introduced through the rock powder must not exceed the P_2O_5 3-year requirements of a given field, to be calculated by the farmer. However, the present guidelines do not allow any rock application exceeding **50% of the P_2O_5 3-year requirements** of a given field.

10.2.2 EU fertilizer product

As per its mean composition (relatively low nutritional content), rock powders do not qualify as solid, inorganic, single-macronutrient *fertilizer* or solid, inorganic, multi-macronutrient *fertilizer* in the sense of PCF1.C.I.a.i, or PCF1.C.I.a.ii. of the regulation (EU) 2019/1009.

Rock powders are defined and approved as *soil conditioners* as per PFC3.B of the (EU) 2019/1009.

Limit values of singe constituents as per (EU) 2019/1009, PFC 3 B, 2-3 must be respected.

Table A3: Label and limit values for soil conditioners under European law

Constituent	Limit value
Cadmium (Cd)	1.5 mg kg-^{1} dry mass
Chromium VI (Cr^{VI})	2 mg kg-^{1} dry mass
Mercury (Hg)	1 mg kg-^{1} dry mass
Nickel (Ni)	100 mg kg-^{1} dry mass
Lead (Pb)	120 mg kg-^{1} dry mass
Inorganic Arsen (As)	40 mg kg-^{1} dry mass
Copper (Cu)	300 mg kg-^{1} dry mass
Zinc (Zi)	800 mg kg-^{1} dry mass

If a given rock powder is to be declared as a European fertilizer product, the given mining company is responsible for relevant characterization, certification, and labelling.

Further, national regulations on product approval and product application, amending European law must be respected.

10.2.3 Rock powder application under U.S. American law

In Preparation

10.2.4 Rock powder application under Brazilian law

In Preparation