Global Rock C-Sink

Guidelines for the Certification of

Carbon Sinks created by Enhanced Rock Weathering in Croplands

Developed by Ithaka Institute for Carbon Strategies, 2022
Version 0.9 (31st October 2022)

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
SPM	Shrinking particle model
Rf	Roughness factor
rSi	Silicon release rate
SSA	Specific surface area
SSA_{BET}	Specific surface area according to Brunauer–Emmett–Teller method
SSA_{GEO}	Geometric surface area based on spherical geometry

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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% 100 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 100 years. This requires instant removal of the total amount of carbon and ensuring uninterrupted, i.e., constant storage for 100 years.
Carbon Expenditures	Carbon expenditures are the greenhouse gases emitted from the process of creating a C-sink, i.e., the carbon footprint of the C-sink. Only if the carbon expenditures in CO_2e are smaller than the CO_2e of the C-sink a net carbon drawdown is achieved.
Climate Service	The removal and a long-term storage of carbon dioxide in time horizons relevant to mitigate anthropogenic climate change, is a climate service. While a C-sink is verifiable at any time by measurement and/or modelling, a climate service shows considerable uncertainties regarding the temporal dynamics, thus no validated C-sink curve exists.
C-Sink Portfolio	A C-sink portfolio is defined as the arithmetic combination of the C-sink curves of C-sinks with different time horizons, at different locations, and/or using different negative emission technologies. A C-sink portfolio serves as an assessment and trading tool to allow the generation C-sinks contributing to the global need for negative emissions. A C-sink portfolio ensures immediate and constant C sequestration for a defined period, of 100 years, following the 100% 100 years principle. C-sink portfolios can be employed to bundle climate services or to combine C-sink curves for CO_2 compensation.
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.
C-Sink Registry	A C-sink registry is a digital, manipulation proved, (potentially block-chain based) database containing certified C-sinks and their respective C-sink curves. A registry can be used as the "library" to compile C-sink portfolios. A registry further contains information regarding the status of C-sink (e.g., *available for sale* or *retired*). C-sink registries, private sector or national, can provide an overview of respective contributions to 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.
Expected C-Sink Curve	A C-sink curve is defined as the function that delivers the amount of carbon stored in a C sink, expressed in tons of C or tons of CO_2e, at any given moment in time. For enhanced rock weathering, the curve is determined by rock powder characteristics and environmental factors such as soil moisture and climate. Due to considerable uncertainties, a C-Sink curve for ERW can only be estimated and is thus not part of the certification. In the certificate, an *Expected-Sink Curve* for preliminary use is provided. This curve must be validated in the future by means of scientifically

	sound and generally accepted models and/or measurements in the field or in reference fields.
Global Cooling Potential	Global cooling potential describes the effect of C-sink, countering global warming potentials of atmospheric greenhouse gases. The global warming potential of 1 t of CO_2e in the atmosphere is balanced by the global cooling potential of 1 t of CO_2e sequestered in a C-sink. Earth system feedbacks to CDR are not considered.
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.
Project Owner	The project owner refers to the party organizing and facilitating an enhanced weathering project and applying for its certification under the present guidelines. The project owner can be a real person e.g., a landowner or farmer or legal person e.g., a company aggregating and coordinating other farmers. The project owner must provide all data requested by the certifier. Typically, the project owner holds the rights to the C-sink certificates generated upon certification.
Rock C-Sink	A generic term, coined to describe C-sinks generated through enhanced weathering of silicate 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 t^{-1} rock or 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.

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1 Short Summary

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 (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, same as amenity values.

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, e.g., with agriculture, as opposed biomass-based negative emission scenarios like short-rotation-copies or afforestation. Instead, ERW is generating agricultural co-benefits by supplying essential macro- and micronutrients, liming effects, and silicon fertilization; supporting plant health, replacing external inputs, and abating 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 is further stabilizing 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 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 certification 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 certification of the **Rock C-Sink potentials as a climate service**, i.e., the amount of carbon that will be removed from the atmosphere at the long term and will be stored as inorganic carbon.

Moreover, the guidelines also define a calculation method for the expected C-Sink curves of ERW-based negative emissions, the sequestration of atmospheric CO_2 as DIC. However, due to the large uncertainty regarding the kinetics of ERW, this is only illustrative and not part of the actual certification, unless the expected C-sink curve is further verified by measurements or modelling approaches that are generally accepted within the scientific community.

While the maximum CDR capacity (CDR_{max}) of a given rock can be well quantified, uncertainty remains regarding the speed, i.e., the field specific rate of the weathering reactions depending on both rock mineralogy and site-specific environmental. As of today, accurate modelling of ERW is still not accomplished and thus conservative proxies and estimates must be used. As a result, the modelled uptake of CO_2 from the atmosphere, quantified in the **expected C-sink curve**, is subject to significant uncertainty.

The centre of the present model forms a modified shrinking particle model, being an established concept for calculating the extent of rock particle weathering at a given time in the future. The model includes:

- Environmental factors, namely soil temperature, soil pH, soil CO_2 concentration and net primary productivity of the region
- A minimum soil moisture threshold below which the model assumes a weathering rate of zero.
- Rock material characteristics, namely particle size distribution, specific surface area and surface roughness factors.

All input parameters and assumptions which determine the model run, are either empirically measured, locally modelled, or arbitrarily chosen in a conservative manner, guaranteeing the maximum timeframe for full rock dissolution with high confidence. True weathering rates are likely faster, however more research is required for verification and validation.

The employed modelling concept aims for substantially reduced complexity, which ameliorates comprehensibility, transparency, feasibility of field specific parametrization. However, to reduce complexity assumptions must be made that may introduce additional uncertainty to the model.

All assumptions are made conservatively, and uncertainties are addressed by safety factors. The model aims to deliver a justified, but sufficiently underestimated expected C-sink curve

The model remains subject to validation. The model will only be regarded as valid if sufficient evidence from field trials confirms that the CDR is not overestimated at any point in time.

Until model validation, or replacement of the employed method, the present guidelines certify only the rock powder application and the Rock C-sink potential that can be monetized as a climate service. However, the provided C-sink potential must not be employed for direct CO_2 compensation until validation of the method (see Chapter 7).

Future research may validate and improve the model, reducing existing safety factors and allowing for less conservative assumptions. The availability of new data will trigger the update or replacement of the present

approach, following rigorous principles of revision and refinement (see Chapter 5.3-5.4 Uncertainties & Outlook).

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 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 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.

To fully monetize the future value of a steadily increasing C-sink curve in an *ex-ante*, yet risk-free manner, the present guidelines deploy the novel concept of C-sink portfolios, i.e., the combination of different negative emissions technologies to create as tradeable climate service. This financial tool deploys the combination of C-sink curves (i.e., the time-depending dynamics of the amount of carbon stored) originating from different types of C-sinks. Herein a decreasing C-sink curve from biochar-based carbon sinks (microbial decay of biochar applied to soil) may be combined with an increasing C-sink curve from Rock-C-sinks (ongoing weathering). Equivalent gains and losses cancel out, to grant a constant and persistent C- sink of the portfolio at any time.

2 Rock and rock powder 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 (lithification) - 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. 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 and admissible rocks

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.

2.1.2 Weathering groups of minerals

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, **the quartz content and the carbonate content must be known**. Quartz is pure silicon dioxide (SiO_2); thus, it is contributing to the SiO_2 pool used for calculations of the silicon-normalized stoichiometric formular, molar mass and volume as described below. However, quartz is barely soluble and if dissolved, it does not release alkalinity and thus does not contribute to carbon dioxide removal

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 quartz or carbonate mineral pools are small, these effects are negligible. If the quartz or carbonate pool is exceeding 2%, it needs to be accounted for through the deduction of the quartz/carbonate minerals from the initial mass balance and elemental composition.

The quartz fraction and the carbonate fraction are determined via bulk mineralogical analysis by X-ray diffraction, as described in Annex 10.1.1.
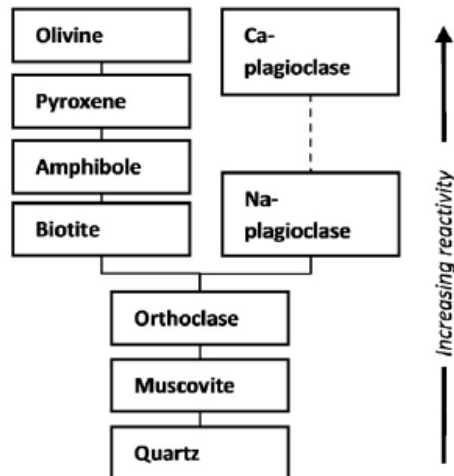
Figure 1: Relative solubility of different mineral classes. Figure adopted from Goldich (1938) and Renforth (2012). Mineral groups at the top have a low degree of silica polymerization and dissolve fast, mineral groups at the bottom have a high degree of silica polymerization and dissolve slower.

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 Calculation of the theoretical carbon dioxide removal capacity of a rock

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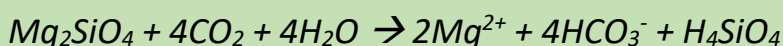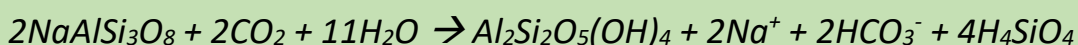
Overall, during mineral weathering one mol of bicarbonate is formed and stabilized per released charge equivalent of available cations (Table 1). Each mol of bicarbonate originating from this reaction process is equivalent to one mol of CO_2 consumed and sequestered from the atmosphere (Lewis et al.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

Thus, CDR_{max} is a function of the metal cation flux released from the weathering process. (Table 1) 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: 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. 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

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

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

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

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

After a reasoned request to Carbon Standards International equation **(1)** may be modified for the application to discrete rock powder production batches, showing relevant concentrations of other metals.

Further, based on the x-ray fluorescence analysis, the silicon-normalized stoichiometric formula of the rock and consecutively the molar weight and molar volume are calculated. For calculation purposes the following 10 oxides as listed in Table 2 (jointly accounting for 97-99% of most rocks mass) are considered:

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Table 2: Molar weight of primary mineral constituents

Oxide	g mol^{-1}
SiO_2	60.09
Al_2O_3	101.96
Fe_2O_3	159.68
MnO	70.94
MgO	40.30
CaO	56.08
Na_2O	61.98
K_2O	94.20
TiO_2	79.87
P_2O_5	141.94

Chapter 2.2.1 - Example 3
Characterization of a basalt rock

Calculations are based on the X-ray fluorescence analysis and pycnometer analysis.

CDR_{max}	0.418
Silicon normalized stoichiometric formular	$Si_1 Al_{0.35} Fe_{0.19} Mn_{0.003} Mg_{0.34} Ca_{0.29} Na_{0.11} K_{0.08} Ti_{0.05} P_{0.01} O_{3.67}$
Molar weight	135.4113 g mol^{-1}
Molar volume	44.54×10^{-6} m^3 mol^{-1}
Density	3.04 g cm^{-3}

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 relevant national and European 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 (as P_2O_5)
- Potassium (as K_2O)
- Magnesium (Mg)
- Sulphur (S)
- Boron (B)
- Copper (Cu)

- Zink (Zi)
- Cobalt (Co)
- Alkaline Components (as CaO equivalents)
- Selenium (Se)
- Chlorine (Cl^-)

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. Adherence to the methods and limit values herein will grant product approval according to respective national or European law and admission under the present guidelines.

Natural mineral rock powders do not contain organic contaminants, thus an analysis for organic contaminants (PFT and PCB) 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 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 to meet e.g., EU definitions. 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 of each production batch of rock powder (see Chapter 8) 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 and consecutive determination of the fraction specific weight and estimation of the fraction specific weighted mean particle diameter, using laser diffraction analysis. Further, all fractions must be subjected to a Brunauer–Emmett–Teller analysis, which quantifies the fraction´s specific surface area in $m^2\ g^{-1}$.

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 model accuracy. 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 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 be met, if the annual precipitation (equivalent to potential soil water infiltration in mm) is larger than the annual potential evapotranspiration (equivalent to potential soil water loss mm). 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 by the project owner. 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):

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

To be admitted under the present guidelines the decadal aridity index of a given location/region must be ≥ 0.75.

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 3.1.1 - Example 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 > 0.75 and qualifies for ERW in cropland applications according to the present standard.

3.1.2 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[2] of 7 (+0.3 units' tolerance above neutrality) is defined here. Thus, a land units initial soil pH must be ≤7.3 to be admissible under the present guidelines. The soil pH must be measured in diluted $CaCl_2$ solution according to the method described in Annex 10.1.

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[2] Refers to the soil pH value measured before rock powder application.

3.1.3 Permanent agricultural land use

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.

The land cannot 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. A deduction from the C-sink potential or a compensation through the retirement of other C-sinks, proportional to the unrealised proportion of the certified C-sink potential must be executed.

3.1.4 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 to national and European fertilizer regulations is 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). 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 10.1.2 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 project owner and/or landowner must ensure appropriate rock powder application rates based on soil and rock powder characterizations.

The analysis for soil contaminants can only be omitted, if the anticipated rock powder application contains less contaminants, then permitted by national or regional regulations as *permitted additional annual load,* (e.g., "Zulässige zusätzliche jährliche Frachten an Schadstoffen" BBodSchv, 1998, Annex 2.5)

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3.2 Material incorporation into soils

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 Chapter 2 exclusively refer to products deployed in the agricultural sector. Rock powder applications to forest land, nature conservation areas and beaches are not covered by the present guidelines.

The method described below (Chapter 5), estimates weathering rates based on abiotic and biotic factors present in the rhizosphere. To grant validity of the method, the present guidelines only cover rock powder applications that were actively incorporated into the topsoil to a minimum depth of 5-10 cm. This can be facilitated through tillage or liquid injection. An incorporation depth of 15-30cm is recommended. However, acknowledging the ecological benefits of conservation tillage such an incorporation depth is not mandatory. A self-propelled downward migration of particles, due to percolation, and bioturbation is expected.

The present guidelines are not covering topsoil applications without consecutive active incorporation, e.g., application to grasslands. Application to non-tilled systems (grassland, miscanthus, bamboo etc.) will only be subject to a later version of this guidelines, due to uncertainties about how long it takes when surface applied rock powder is incorporated into the soil.

Rock powder application to perennial agricultural systems can be covered by the present guidelines if active rock powder incorporation or injection is caried out.

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 relevant national 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 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 applicant 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 project owner (written information to the farmers about the nutrient load per hectare of the planned application, not applicable if the applying farmer and the project owner are the same person).

The present guidelines recommend to not exceed a nutrient load of 30 kg P_2O_5 ha^{-1} year^{-1}, but define a definite limit to the applied P_2O_5 loads, equalling 50-% of the 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) before the rock powder application. The project owner 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.

Chapter 3.3 - Example 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 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.

3.4 Application techniques

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). Rock powders in the particle range of 0-2000 μm may be stored outside and can be subject to rain.

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).

4 Environmental factors impacting rock weathering

In the field, weathering rates are influenced by a complex array of environmental factors. The present method attempts to break down these complex phenomena into a set of comprehensible and transparent, yet robust determining factors.

Abiotic factors are soil temperature, soil moisture, soil pH and soil CO_2 concentration, while biotic factors are bulk biogenic weathering agents such as organic acids, microbes, earthworms, etc.

4.1 Agroclimatic data and climate change

To guarantee that a specific location is suitable for ERW and to calculate a location specific expected weathering rate, a set of agroclimatic variables is required, namely soil temperature and soil moisture as specified below. The project owner must provide this information, along with its source. The certification body examines the data for plausibility and verifies its source.

Generally, data can be obtained from regional monitoring 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 monitoring station, reference location or grid cell must be deployed.

In the examples used to illustrate this guideline data from the German Meteorological Service / "Deutscher Wetterdienst" database (DWD, 2022) is used.

Accounting for future climate change: Climate models are still constrained to a comparably low spatial resolution. Not all required parameters can be approximated well and models are hardly usable by lay persons. To ensure high spatial resolution and open access to the required data, the present guidelines establish a conservative extrapolation approach, relying on past climate data. The year indicating the lowest mean national or sub-national precipitation during the last decade before rock powder application will be chosen as the baseline year to extract climate data and conservatively approximate future conditions.

4.2 Soil temperature

The surrounding soil temperature is a main factor that determines the *in-situ* weathering rate of silicate rock (see Chapter 5.1). Weathering rates and soil temperature are positively corelated. For calculation purpose, the mean annual soil temperature measured or modelled for a depth between 10-30 cm, for the location of rock powder application or closest reference location or grid cell must be identified. The annual mean is calculated as the mean of 365 daily values or 12 monthly values. The reference year to be selected for this calculation must be the year with the lowest mean national or sub-national precipitation of the last decade before the rock powder application. If the mean monthly soil temperature is ≤ 0°C for one or several months, this value is not considered in the calculation of the mean, however the respective number of months is deducted from the number of *valid months* as per Chapter 4.3. Where data availability permits, the same soil depth should be used to derive data on soil moisture and soil temperature. The difference in depth must not exceed 10 cm.

4.3 Soil moisture

The presence of water as soil moisture is a prerequisite for the occurrence of chemical weathering.
A clear and universal correlation between weathering rate and ambient soil moisture (%) or precipitation (mm) is not yet established and remains subject to further research. The present method retreats to a simplified concept of *valid months*. A valid month is defined as a month in which the soil water status is considered not limiting for soil biology and weathering reactions. In these months weathering according to the modelled rate occurs. If the threshold is not met, the weathering rates are set to 0.

The mean monthly soil moisture measured or modelled for a depth of 10-30 cm, for the location of rock powder application or closest reference location or grid cell must be identified. The soil moisture can be expressed in relative plant available field capacity or relative volumetric soil water content. Soil moisture thresholds are preliminary set to ≥ 50% available field capacity or equivalent volumetric soil water content of ≥ 6.25% (sandy soils), ≥ 13.75% (loamy soil) and ≥ 16.25% (clayey soil). The conversion of available field capacity to volumetric soil water content is based on mean values provided by the Cornell University Extension Service (NRCCA, 2022). The number of months per year, exceeding the given threshold must be identified and will serve as the *valid month nominator* in later calculations (see Chapter 5.1). The reference year to be selected for this calculation must be the year with the lowest mean national or sub-national precipitation of the last decade before the rock powder application. Where data availability permits, the same soil depth should be used to derive data on soil moisture and soil temperature. The difference in depth must not exceed 10 cm.

4.4 Soil pH

The soil pH is a main factor influencing *in-situ* weathering rates of silicate rock (see Chapter 5.1). Generally, weathering rates are rather low at circumneutral soil pH values and accelerate with decreasing pH (acidic soil conditions), for most minerals. The soil pH refers to the 0-30 cm soil horizon and is to be measured as pH-$CaCl_2$ according to Annex 10.1.2 before rock powder application. Soil samples for analysis must be drawn according to the soil sampling protocol in Annex 10.1.2

Chapter 4.3 - Example 6
Required location-specific agroclimatic data

For a rock powder application carried out in 2022 in Germany, the year 2018 being the dryest of the last decade, is selected as the reference year

For a reference location in Ohlsbach, in the Ortenau district in Germany, the following data can be sourced from reference location 1602 of the database of German Meteorological Service /"Deutscher Wetterdienst":

Mean annual soil temperature at 20 cm depth = 14.1 °C
Valid month nominator based on % AFC at 20 cm depth = 7
Months with mean annual soil temperature ≤ 0°C = 0

4.5 CO₂ partial pressure in the rhizosphere

Beside temperature moisture and pH, covered above, the surrounding CO_2 partial pressure is a key parameter controlling the weathering rate. CO_2 dissolves in water in an equilibrium reaction, balancing concentrations of dissolved CO_2 and ambient gaseous CO_2. Any increase in ambient CO_2 concentrations will directly increase the concentration of carbonic acid in solutions being exposed to this environment. Consecutively, the dissolution of rocks exposed to the solution is accelerated (Kelland et al., 2020; Renforth and Campbell, 2021). Increasing ambient CO_2 concentrations to 1,000,000 ppm (100% CO_2 saturation) can increase rock weathering - and CDR rate by a factor of > 4 compared to atmospheric CO_2 levels (Amann et al., 2022). Due to autotrophic and heterotrophic respiration, the partial pressure of CO_2 is always higher in the rhizosphere than those in the atmosphere and can exceed atmospheric levels by two orders of magnitude (Upadhyay et al. 2021; Renforth and Campbell, 2021). In temperate soils, concentrations of >10,000 ppm CO_2 can be observed (Project Carbdown, *in preparation*), however in the tropic's concentrations can increase up to 70,000 ppm CO_2 (Davidson and Trumbore, 2017).

The function (Fig. 3) is derived from data presented in Amann et al. (2022) and serves as the generic estimator for the CO_2 driven weathering rate scaling factor. The respective CO_2 concentration at 10-30 cm depth is deployed as the parameter on the x-axis in the derived regression function. The pH and temperature determined weathering rate, determined through the silicon release model (Chapter 5.1), is corrected by multiplication with the CO_2 rate scaling factor.
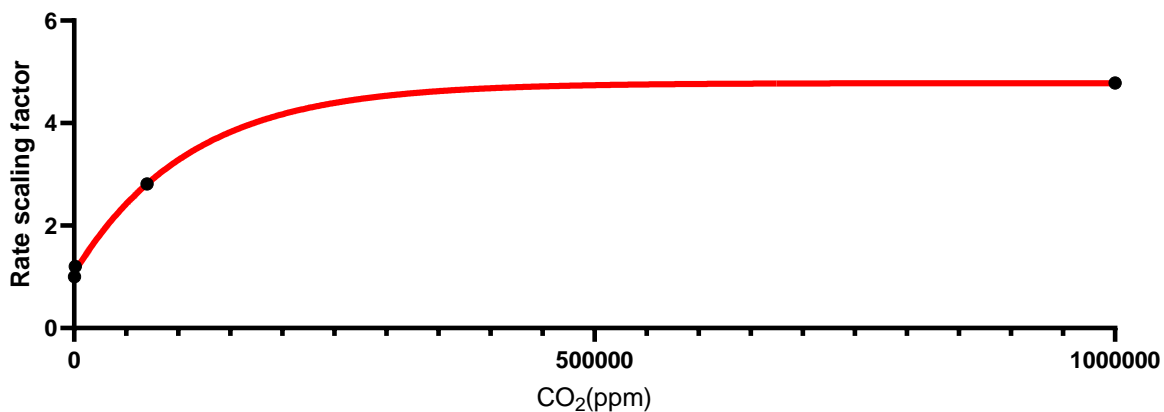
Figure 3: Influence of elevated CO_2 in the rhizosphere. Plotted function of weathering rate scaling factor r(CO_2) according to equation (3), based on data presented in Amann et al. (2022). R^2 = 0.99.

Equation (3):

$$r(CO_2) = 1.076 * e^{9.029 * 10^{-6} * x}$$

x= Soil CO_2 concentration at 10-30 cm depth in ppm

For most locations, there are no empirical values on mean annual soil CO_2 concentrations available. In such case the following default values (Table 4) apply.

Table 4: Default values for the weathering rate scaling factor r(ppmCO$_2$)

Climate	CO$_2$ concentration in the rhizosphere (ppm)	Rate scaling factor r(CO$_2$)
Temperate moist	8.000	1.334
Sub-tropical	25.000	1.808
Tropical	40.000	2.720

4.6 Biogenic weathering agents

All rate modifying factors as described above (temperature, pH, CO_2) are of abiotic nature. Their influences can be well isolated and studied in controlled column experiments (e.g., Amann et al., 2022) or mixed-flow reactors (e.g. Gudbrandsson et al., 2011). However, weathering rates purely governed by abiotic factors are not representative for ERW application on croplands. In open land systems, the applied rock powder is exposed to additional biogenic weathering agents imposed by rhizosphere processes. Rhizosphere processes can increase weathering rates and consecutively CDR rates (Krahl, 2020; Verbruggen et al., 2021). Also, permanent occlusion of rock particles and secondary mineral coating may be prevented through such biogenic agents, including microbes and earthworms (Lidermann et al., 2000; Buss et al., 2007; Torres et al., 2019; Vicca et al., 2022).

The sum of biotic effects is approximated by an empirical function (Fig. 4) generated by Beerling et al. (2020), based on studies by Akter and Akagi (2005); Akter and Akagi (2010); Quirk et al. (2012) and Quirk et al. (2014). Herein, the normalized net primary productivity (NPP$_{norm}$) of a given region serves as the predictor for a second weathering rate scaling factor.

This factor represents the bulk effect of multiple rhizosphere processes that accelerate the fragmentation and chemical dissolution of mineral grains, including the activities of mycorrhizal structures, organic acids and chelating agents causing disruption and chemical etching of rock surfaces.

The overall scarcity of data regarding these processes needs to be acknowledged. Yet the influence of plants and the rhizosphere is relevant to an extent that these processes must be included to determine conservative estimates for ERW in croplands (Amann et al., 2022).
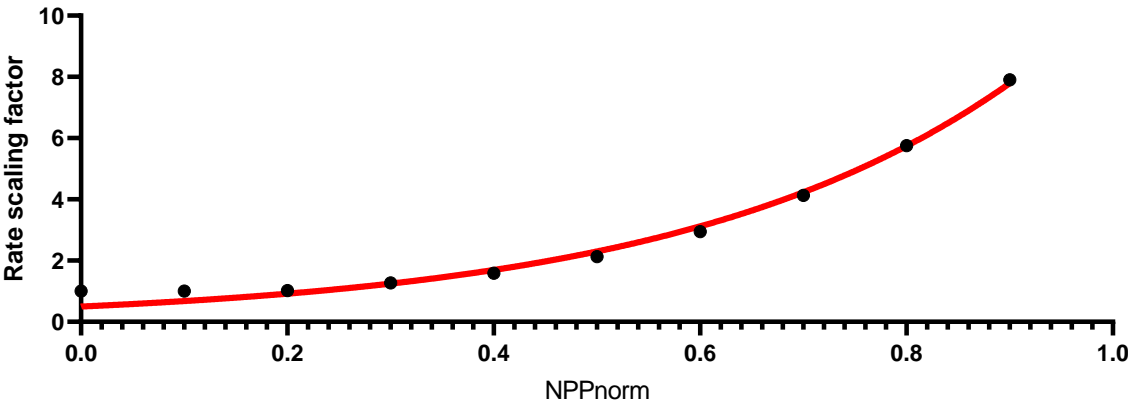
Figure 4: *Influence of biogenic weathering agents. Plotted function of weathering rate scaling factor r(NPPnorm) according to equation (4), based on data presented in Beerling et al. (2020) and function parameters for annual cropping systems.*

Equation (4):

$$r(NPPnorm) = a * (xnorm * NPPnorm)^b + 1$$

Annual cropping systems   *Perennial cropping systems*
a = 0.140386   **a** = 0.065906
b=3.54559   **b**=1.48934
xnorm= 3   **xnorm**= 18

NPPnorm = *normalized NPP index (0-1)*
Equation: Beerling et al. (2020)

Raster data (e.g. Fig. 5 and 6) containing input variables to the above formula will be provided through Annex 10.3. Until the publication of Annex 10.3, for central European locations, a conservative NPP_{norm} value of **0.6** and **0.2** is used for annual and perennial cropping systems respectively.

Figure 5: *Global overview of NPP_{orm} of annual cropping systems (Source Fig. 6: Modified from Beerling et al. 2020).*

Figure 6: *Global overview of NPP$_{norm}$ of perennial cropping systems (Source Fig. 6: Modified from Beerling et al. 2020).*

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5 Modelling of the weathering process

The present modelling approach is following the principle of reduced model complexity. The calculations are such that the CDR potential tends to be underestimated. The core of the model is derived from laboratory experiments, investigating silicate rock dissolution at far from equilibrium conditions. Transferring such laboratory results to field conditions implies assumptions, model limitations, and a fair uncertainty.

Model assumptions and limitations are summarized in the **orange box**, at the end of the chapter. **As a direct consequence of the implied uncertainties, the C-sink potential must not yet be traded in the context of CO₂ compensation schemes (see Chapter 5.3 Uncertainties and Chapter 7 Valorization of C-sink potentials).**

5.1 Standardization of multi mineral weathering to as silicon release model

Many research studies targeted dissolution rates of single mineral species. Different mineral species exhibit contrasting dissolution behaviours. Given the same ambient temperature, the dissolution speed varies between different mineral species. The same holds for the dissolution rate as a function of pH. Further, the amount of bicarbonate generated by the reaction varies between different mineral species, as determined by the amount and valance of metals released. As such, single mineral dissolution rates are only valid in scenarios of application of pure or quasi-pure minerals, e.g., forsterite (e.g., Hangx and Spiers, 2009).

However, most available silicate rocks are composed of multiple minerals. There are advances in the development of process-based models (see Chapter 5.4 Outlook), to approximate the bulk weathering of multi-mineral rocks. Geochemical models, e.g., PhreeqC (Parkhurst and Appelo, 1999), sum up the mineral specific dissolution (rates/products) to estimate the overall rock dissolution. State of the art models, such as SCEPTER (Kanzaki et al. 2022) can simulate up to 39 individual mineral species. Nevertheless, until today there is no process-based model that is fully validated or accredited for C-sink accounting. Analytics required to provide the required high resolution input data to the model may render operations cost prohibitive.

In general, complex models must be reviewed with caution. With increasing complexity (i.e., increasing number of factors to be set and assumptions to be made) the potential for overfitting arises. This means that, a model can be parameterized to generate a desired result, rather than objectively predicting a realistic result. This risk can be minimized by reducing complexity, using only a small number of robust predictors, or when the parameterization boundaries of complex models are rigorously regulated.

Rather than deploying a multi-mineral model, the present method utilizes the concept of a silicon normalized weathering model. Regardless of their dissolution speed and elemental composition, minerals contained in rock types eligible for ERW application (olivine, pyroxene, plagioclase, etc.) contain silicon. Upon successful dissolution of the primary mineral, silicon is released to the solution as an aqueous species (or forms secondary clay particles). Dissolved silicon can serve as a proxy for a multi-mineral weathering rate. Standardizing a silicate rock composition to a silicon-normalized stoichiometric formula, same as silicon-normalized molar weight and volume, the overall mass of rock weathered can be approximated from the silicon release – irrespectively of the silicon's fate.

Aluminosilicates show a synclinal release of silicon as a function of pH (Gislason and Oelkers 2003; Gudbrandsson et al. 2011; Rinder and Hagke 2021). Under acidic conditions the release rate decreases with

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increasing pH. Under neutral to alkaline conditions the release rate increases with increasing pH. The lowest weathering rate can thus be observed at circumneutral conditions. The release rate is positively correlated to the ambient temperature.

For the construction of a generic silicon release model, empirical data from a series of 26 silicate rock dissolution experiments, conducted by Gudbrandsson et al. (2011) was utilized. The experiments used crystalline[3], Icelandic basalt which, based on its elemental and mineral composition [∑ (olivine, plagioclase, pyroxene, K-feldspar) ≥ 50wt%], qualifies to serve as a model silicate rock in this context. Steady state dissolution experiments were carried out in a mixed-flow reactor (no water limitation conditions), covering a temperature range from 5°C to 75°C and a pH range from 2 to 11. The surface area normalized silicon release rate was calculated as a robust mean from multiple measurements from each of the 26 experiments.

The present guidelines exclude rock powder applications to fields of alkaline soil pH. Thus, data from experiments conducted under acidic to neutral conditions were extracted from Gudbrandsson et al. (2011) and subjected to non-linear regression analysis to derive a generic model, estimating the silicon release (rSi) in *mol Si cm^{-2} s^{-1}* as a function of ambient temperature and pH.

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[3] Basalt is an igneous rock from volcanic origin. Whether basalt is referred to as crystalline- basalt or basalt glass depends on the arrangement of minerals (rather crystalline structure or amorphous structure, respectively). The latter is determined by the speed of solidification / cooldown of magma. Data from Gudbransson et al (2011) was compared to data from Gislason and Oelkers (2003) who investigated basaltic-glass dissolution. The elemental composition and silicon normalized dissolution rate are comparable.

Regression model for acidic soil condition (applicable if soil pH ≤ 7)

Equation (5):

$$\log(rSI) = 0.1106x^2 - 1.5573x + 0.0234z - 10.6245$$

x = pH; significant contribution of the predictor p<0.001
z = Soil temperature in °C; significant contribution of the predictor p<0.001
Model adjusted R²= 0.91

Chapter 5.1 - Example 7
Calculation of the silicon release rate from multi-mineral silicate rocks

A farm in the Ortenau region has a soil pH of 6.6 and a mean annual soil temperature of 14.1 °C

$$\log(rSi) = 0.1106 * 6.6^2 - 1.5573 * 6.6 + 0.0234 * 14.1 - 10.6245$$

$$\log(rSi) = -15.7559$$

$$rSi = 10^{-15.7559} \, mol \, Si \, cm^2 \, s^{-1}$$

For soil pH in the range of 7.1-7.3 (tolerance range) the rSi of pH 7 and the site-specific temperature is used (Fig. 7).

Model Assumptions

The model employs primary data from a laboratory experiment investigating the dissolution behaviour of an Icelandic basalt rock. This silicate rock presenting a mineral composition of ∑ (olivine, plagioclase, pyroxene, K-feldspar) ≥ 50wt% serves as a **model rock** exposed to varying environmental conditions. The present modelling approach employs assumptions only valid for long time horizons, as e.g., the 100-year time horizon of the C-sink portfolio approach (see Chapter 7.2). Over long time periods (several decades) a mean congruent element loss from the primary particles is assumed. It is further assumed that the pH at particle surface can be approximated through the initial soil bulk pH when a time horizon of several seasons is considered

Long term congruent element loss from the primary silicate

Although the aqueous weathering products of a reaction may not express the composition of a congruent dissolution, since, e.g., aluminium may be preserved in solid secondary products, the element loss – and thus mass loss - from the primary silicate rock particle occurs congruently to the long-term mean.

$$(Si/element)_{primary\text{-}solid} / (Si/element)_{secondary\text{-}solid + aqueous\text{-}solution} = 1$$

When observing particle dissolutions over short periods (e.g., in laboratory experiments) an incongruent dissolution determined by different solubilities of different minerals can be observed. Also, if only comparisons between $(Si/element)_{primary\text{-}solid}$ / $(Si/element)_{aqueous\text{-}solution}$ are conducted, the identified ratio may point towards incongruent dissolution, as some elements may be preserved in a solid phase of secondary minerals as, e.g., in kaolinite.

Nevertheless, in the long-term, the primary particle will dissolve congruently. A long-term incongruent dissolution would leave behind a primary mineral particle consisting of either 0% Si or 100% Si, both cases are not observed. For the present, method using silicon release as a proxy for mass loss (not as a proxy for alkalinity released into solution), only a congruent mass loss from the primary particle (long-term mean) is relevant, not a congruent release of dissolved ions.

Ambient pH at particle surface

The model assumes, that on average the primary silicate rock particle is experiencing an ambient pH, that is equivalent to the ambient bulk soil pH (0-30cm, standard plough-pan depth). It is evident, that as a direct result of rock weathering, the ambient pH at the particle surface increases. This is determined by the released alkaline weathering products. Yet, it is also given, that this modification of the ambient pH is only occurring in a discrete soil volume, which is in constant or intermittent exchange with the remaining bulk soil solution.

Example: A standard loam soil has a bulk density of 1.30 g cm³ (3900 t, or 3000 m³ soil ha⁻¹ at 0-30cm depth). The field will be amended with 20 t rock powder ha⁻¹, having a bulk density of 1.45 g cm³ (13.33 m³ ha⁻¹). The introduced rock powder will only contribute and directly affect ~0.4% of the soil volume, which remains in constant exchange with the remaining ~99.6% soil volume and respective soil solution, that is exhibiting the chemical baseline conditions. It is further evident, that weathering products, as alkalinity, are subject to removal by percolating water (rainwater infiltration).

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The silicon release rate as determined through the generic model is corrected using the rate scaling factors rCO_2 (rhizosphere CO_2 Chapter 4.5), $rNPP_{norm}$ (biogenic weathering agents Chapter 4.6) and the *valid month nominator* (moisture limitations Chapter 4.3) according to equation **(6).**

Equation (6):

$$rSi\_corrected = rSi * r(CO2) * r(NPPnorm) * \frac{Valid\ Months}{12}$$

rSi_corrected = silicon release rate after correction for additional environmental factors.
rSi = silicon release rate based on the multimineral weathering model (Chapter 5.1)
rCO$_2$ = weathering rate scaling factor based on rhizosphere CO_2 concentration
rNPPnorm = weathering rate scaling factor based on biogenic weathering agents
Valid months = months with sufficient soil moisture

The corrected silicon release rate (mol Si cm^{-2} s^{-1}) will be converted to mol Si m^{-2} y^{-1} and inserted into a modified SMP model as described in Chapter 5.2

Overview:

Logarithm of the silicon release rate as determined by soil temperature and soil pH

		Mean Annual Soil Temperature															
		5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Soil pH	7.3	-15.9877	-15.9643	-15.9409	-15.9175	-15.8940	-15.8706	-15.8472	-15.8238	-15.8004	-15.7770	-15.7536	-15.7302	-15.7068	-15.6834	-15.6599	-15.6365
	7.2	-15.9877	-15.9643	-15.9409	-15.9175	-15.8940	-15.8706	-15.8472	-15.8238	-15.8004	-15.7770	-15.7536	-15.7302	-15.7068	-15.6834	-15.6599	-15.6365
	7.1	-15.9877	-15.9643	-15.9409	-15.9175	-15.8940	-15.8706	-15.8472	-15.8238	-15.8004	-15.7770	-15.7536	-15.7302	-15.7068	-15.6834	-15.6599	-15.6365
	7	-15.9877	-15.9643	-15.9409	-15.9175	-15.8940	-15.8706	-15.8472	-15.8238	-15.8004	-15.7770	-15.7536	-15.7302	-15.7068	-15.6834	-15.6599	-15.6365
	6.9	-15.9857	-15.9623	-15.9389	-15.9155	-15.8921	-15.8687	-15.8453	-15.8219	-15.7985	-15.7750	-15.7516	-15.7282	-15.7048	-15.6814	-15.6580	-15.6346
	6.8	-15.9816	-15.9582	-15.9347	-15.9113	-15.8879	-15.8645	-15.8411	-15.8177	-15.7943	-15.7709	-15.7475	-15.7241	-15.7006	-15.6772	-15.6538	-15.6304
	6.7	-15.9752	-15.9518	-15.9284	-15.9050	-15.8816	-15.8581	-15.8347	-15.8113	-15.7879	-15.7645	-15.7411	-15.7177	-15.6943	-15.6709	-15.6475	-15.6240
	6.6	-15.9666	-15.9432	-15.9198	-15.8964	-15.8730	-15.8496	-15.8261	-15.8027	-15.7793	-15.7559	-15.7325	-15.7091	-15.6857	-15.6623	-15.6389	-15.6155
	6.5	-15.9558	-15.9324	-15.9090	-15.8856	-15.8622	-15.8387	-15.8153	-15.7919	-15.7685	-15.7451	-15.7217	-15.6983	-15.6749	-15.6515	-15.6281	-15.6046
	6.4	-15.9428	-15.9194	-15.8960	-15.8726	-15.8491	-15.8257	-15.8023	-15.7789	-15.7555	-15.7321	-15.7087	-15.6853	-15.6619	-15.6385	-15.6150	-15.5916
	6.3	-15.9276	-15.9041	-15.8807	-15.8573	-15.8339	-15.8105	-15.7871	-15.7637	-15.7403	-15.7169	-15.6935	-15.6700	-15.6466	-15.6232	-15.5998	-15.5764
	6.2	-15.9101	-15.8867	-15.8633	-15.8399	-15.8165	-15.7931	-15.7697	-15.7462	-15.7228	-15.6994	-15.6760	-15.6526	-15.6292	-15.6058	-15.5824	-15.5590
	6.1	-15.8905	-15.8671	-15.8436	-15.8202	-15.7968	-15.7734	-15.7500	-15.7266	-15.7032	-15.6798	-15.6564	-15.6330	-15.6095	-15.5861	-15.5627	-15.5393
	6	-15.8686	-15.8452	-15.8218	-15.7984	-15.7750	-15.7515	-15.7281	-15.7047	-15.6813	-15.6579	-15.6345	-15.6111	-15.5877	-15.5643	-15.5409	-15.5174
	5.9	-15.8445	-15.8211	-15.7977	-15.7743	-15.7509	-15.7275	-15.7041	-15.6806	-15.6572	-15.6338	-15.6104	-15.5870	-15.5636	-15.5402	-15.5168	-15.4934
	5.8	-15.8182	-15.7948	-15.7714	-15.7480	-15.7246	-15.7012	-15.6778	-15.6544	-15.6309	-15.6075	-15.5841	-15.5607	-15.5373	-15.5139	-15.4905	-15.4671
	5.7	-15.7897	-15.7663	-15.7429	-15.7195	-15.6961	-15.6727	-15.6493	-15.6259	-15.6024	-15.5790	-15.5556	-15.5322	-15.5088	-15.4854	-15.4620	-15.4386
	5.6	-15.7590	-15.7356	-15.7122	-15.6888	-15.6654	-15.6420	-15.6185	-15.5951	-15.5717	-15.5483	-15.5249	-15.5015	-15.4781	-15.4547	-15.4313	-15.4079
	5.5	-15.7261	-15.7027	-15.6793	-15.6558	-15.6324	-15.6090	-15.5856	-15.5622	-15.5388	-15.5154	-15.4920	-15.4686	-15.4452	-15.4217	-15.3983	-15.3749
	5.4	-15.6909	-15.6675	-15.6441	-15.6207	-15.5973	-15.5739	-15.5505	-15.5271	-15.5037	-15.4802	-15.4568	-15.4334	-15.4100	-15.3866	-15.3632	-15.3398
	5.3	-15.6536	-15.6302	-15.6068	-15.5834	-15.5599	-15.5365	-15.5131	-15.4897	-15.4663	-15.4429	-15.4195	-15.3961	-15.3727	-15.3493	-15.3258	-15.3024
	5.2	-15.6140	-15.5906	-15.5672	-15.5438	-15.5204	-15.4970	-15.4736	-15.4501	-15.4267	-15.4033	-15.3799	-15.3565	-15.3331	-15.3097	-15.2863	-15.2629
	5.1	-15.5722	-15.5488	-15.5254	-15.5020	-15.4786	-15.4552	-15.4318	-15.4084	-15.3850	-15.3615	-15.3381	-15.3147	-15.2913	-15.2679	-15.2445	-15.2211
	5	-15.5282	-15.5048	-15.4814	-15.4580	-15.4346	-15.4112	-15.3878	-15.3644	-15.3410	-15.3176	-15.2941	-15.2707	-15.2473	-15.2239	-15.2005	-15.1771
	4.9	-15.4820	-15.4586	-15.4352	-15.4118	-15.3884	-15.3650	-15.3416	-15.3182	-15.2948	-15.2713	-15.2479	-15.2245	-15.2011	-15.1777	-15.1543	-15.1309
	4.8	-15.4336	-15.4102	-15.3868	-15.3634	-15.3400	-15.3166	-15.2932	-15.2697	-15.2463	-15.2229	-15.1995	-15.1761	-15.1527	-15.1293	-15.1059	-15.0825
	4.7	-15.3830	-15.3596	-15.3362	-15.3128	-15.2893	-15.2659	-15.2425	-15.2191	-15.1957	-15.1723	-15.1489	-15.1255	-15.1021	-15.0787	-15.0552	-15.0318
	4.6	-15.3301	-15.3067	-15.2833	-15.2599	-15.2365	-15.2131	-15.1897	-15.1663	-15.1429	-15.1195	-15.0960	-15.0726	-15.0492	-15.0258	-15.0024	-14.9790
	4.5	-15.2751	-15.2517	-15.2283	-15.2049	-15.1815	-15.1580	-15.1346	-15.1112	-15.0878	-15.0644	-15.0410	-15.0176	-14.9942	-14.9708	-14.9474	-14.9239
	4.4	-15.2178	-15.1944	-15.1710	-15.1476	-15.1242	-15.1008	-15.0774	-15.0540	-15.0305	-15.0071	-14.9837	-14.9603	-14.9369	-14.9135	-14.8901	-14.8667
	4.3	-15.1583	-15.1349	-15.1115	-15.0881	-15.0647	-15.0413	-15.0179	-14.9945	-14.9711	-14.9477	-14.9242	-14.9008	-14.8774	-14.8540	-14.8306	-14.8072
	4.2	-15.0966	-15.0732	-15.0498	-15.0264	-15.0030	-14.9796	-14.9562	-14.9328	-14.9094	-14.8860	-14.8625	-14.8391	-14.8157	-14.7923	-14.7689	-14.7455
	4.1	-15.0327	-15.0093	-14.9859	-14.9625	-14.9391	-14.9157	-14.8923	-14.8689	-14.8455	-14.8221	-14.7986	-14.7752	-14.7518	-14.7284	-14.7050	-14.6816
	4	-14.9666	-14.9432	-14.9198	-14.8964	-14.8730	-14.8496	-14.8262	-14.8028	-14.7793	-14.7559	-14.7325	-14.7091	-14.6857	-14.6623	-14.6389	-14.6155

Figure 7: Overview of log(rSi) as a function of soil pH and soil temperature. Minimal weathering rates are achieved at neutral soil pH and low temperatures. Highest weathering rates are achieved under low soil pH and high soil temperatures. For soil pH values between 7-7.3 (soil pH tolerance margin) weathering rates equivalent to pH 7.0 are deployed.

5.2 A modified shrinking particle model

There are two basic concepts to determine the specific surface area (SSA) of a rock particle. Commonly used are empirical measurements of the SSA using N_2 gas-adsorption and an evaluation of the sorption isotherm using the Brunauer–Emmett–Teller (BET) method called SSA_{BET} (Gudbransson et al., 2011; Lewis et al., 2021). An alternative approach is the conceptualization of particles as symmetric spheres and the calculation of SSA_{GEO} based on sphere geometry and material density. In both cases, the SSA is commonly reported as $m^2\,g^{-1}$. To unify SSA and weathering rate units, the SSA needs to be converted to $cm^2\,g^{-1}$.

During weathering, the rock particles undergo structural changes which include the evolution of SSA. Until today, there is no comprehensive data on the SSA evolution of rock particles exposed to abiotic- and biotic weathering in a cropland environment.

The *"best-case"* scenario is the formation of etch pits (e.g. Monasterio-Guillot et al. 2021) as weathering progresses. Under this assumption the SSA would tend to increase over time (Fig. 8).

The *"worst-case"* scenario is the formation of inert layers of secondary weathering products, blocking the reactive surfaces and leading to a passivation of the rock particle (e.g., Deng et al. 2022). Amann et al. (2020) hypothesized, that a cation depleted silicon layer is forming on the surface of minerals from dunite rock, exposed to near *in-situ* weathering conditions in a mesocosm experiment. Stockmann et al. (2011, 2013) investigated, if secondary surface precipitates, in particular carbonates as calcite, alter the dissolution kinetics of basaltic glass or diopside (pyroxene, a chain silicate). Their abiotic mixed-flow-reactor studies reveal that calcite tends to form as discrete crystals not as pervasive layers. If layer-like structures occur, they are mostly porous, allowing for the exchange of ions with the soil bulk fluid. Within the context of these studies, no impact of secondary phases on the overall rock dissolution rate could be identified. It is likely that additional etching effects of biogenic agents further support this trend and avoid particle passivation (Chapter 4.6).

As a conservative midway approach, the present guidelines will deploy the concept of a shrinking particle model, modified from Hangx and Spiers (2009) and Rinder and Hagke (2021).
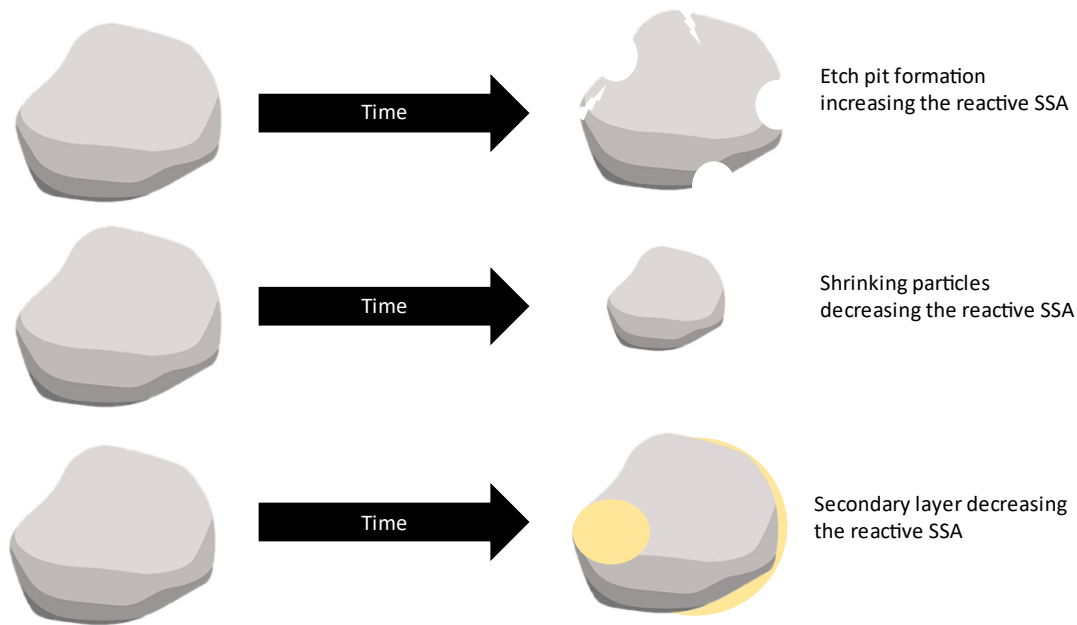
Figure 8: Schematic overview of possible particle surface evolution pathways. Top: An increase in reactive specific surface area (SSA) because of chemical etching, resulting in the formation of pits. Middle: A decrease in reactive SSA proportional to its mass loss, approximating particle geometry through a round sphere. Bottom: A decrease in reactive SSA due to the inertisation of reaction sides through secondary precipitates or occlusion of rock particles in other matter.

A shrinking particle model translates the mass loss from a rock particle (due to weatheirng) into a proportional decrease in reactive surface area, based on a known material density and the assumption of spherical particles (Hangx and Spiers, 2009). The SSA_{GEO} of such spherical particles is calculated according to **Equation (7).**

However, rock particles are not spherical and simplified SSA_{GEO} models are neglecting the fractures, elevations and porosities of rock particle surfaces. To address this issue the concept of a surface roughness factor (Rf) was introduced (e.g. Navarre-Sitchler et al., (2007)). The Rf is calculated according to **Equation (8)** as the ratio between the measuered SSA_{BET} and the calculated $SSA_{GEO.}$

After that, the rSi (Chapter 5.1) is multiplied with the Rf according to **Equation(9).**

The Rf-corrected rSi is given the rSi_{GEO}, which is used in the SPM as given in **Equation (10).**

The shrinking particle model (SPM)

Equation (7)

$$SSA_{GEO} = \frac{6}{d\rho}$$

(Tester et al. 1994)

SSA$_{GEO}$ *= Geometric SSA in cm² g $^{-1}$*
6 *= constant relating to spherical shape*
d *= effective particle diameter (weighted mean of particle size class) in cm*
p *= Rock density in g cm^{-3}*

Equation (8)

$$Rf = \frac{SSA_{BET}}{SSA_{GEO}}$$

(Rinder and Hagke 2021)

Rf *= Roughness factor; unitless*
SSA$_{BET}$ *= SSA measured via BET in cm² g $^{-1}$*
SSA$_{GEO}$ *= SSA calculated according to equation (7)*

Equation (9)

$$r_{Si\_GEO} = r_{Si} * Rf$$

(Rinder and Hagke 2021)

rSi$_{geo}$ *= Roughness factor corrected rate mol m^{-2} year $^{-1}$*
rSi *= BET normalized rate as determined form the silicon release model in mol m² $^{-1}$ year $^{-1}$*
Rf *= Roughness factor; unitless. Calculated according to equation (8)*

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Equation (10)

$$X_{Rock(t)} = \frac{d_0^3 - (d_0 - 2rSi_{geo}\Omega t)^3}{d_0^3} * 100$$

(Hangx and Spiers 2009)
(Rinder and Hagke 2021)

X_Rock**(t)** = *fraction of rock grain weathered at time t*
d₀ = *initial particle diameter in m*
rSi_geo **= = Roughness factor corrected rSi**
in mol m⁻² year⁻¹. Calculated according
to equation (9)
Ω = *The molar volume of the rock in m³ mol⁻¹*
t = *time since application in years*

To apply a SPM to a cohort of particles, e.g., 1 t of rock powder, **Equation (10)** must be solved for each particle size class (using the weighted mean particle diameter of the fraction, Annex 10.1.1, as initial particle diameter d_0). The result is then converted into tons of weathered rock by multiplying it with the initial mass of the considered fraction. At last, a summation of the rock masses weathered in all size classes is carried out. These operations are summarized in **Equation(11)**.

Equation (11):

$$Rock\ powder\ mass\ weathered\ (t) = \sum_{i=1}^{n} m_i * \frac{d_{0i}^3 - (d_{0i} - 2rSi_{geo}\Omega t)^3}{d_{0i}^3}$$

Rock powder mass weathered(t) = Mass of dissolved rock powder at time t
n = number of characterized particle size fractions
i = index value of the fraction
m_i = initiall mass of fraction i in tons rock powder
d_i = weighted mean particle diameter of fraction i in meter
rSi_{geo} = Roughness factor corrected rSi
in mol m^{-2} year $^{-1}$. Calculated according
to equation (9)
Ω = The molar volume of the rock in m³ mol $^{-1}$
t = time in years

The rock powder mass weathered at time t is now transelated in % of rock mass weatherd at time t, through a division by the initiall rock mass. A further multiplication with CDR_{max} yields the time dependent C-sink, as sumarized in equation (12).

Equation (12):

$$Gross\ Rock\ C\ Sink\ (t) = CDR_{max} * \frac{Rock\ powder\ mass\ weathered\ (t)}{initial\ rock\ mass}$$

Gross Rock C-Sink = The gross rock C-sink in tons CO_2 ton^{-1} rock powder at time t
CDR_{max} = Maximum carbon dioxide removal in t CO_2 ton^{-1} rock powder
Rock powder mass weathered(t) = Mass of dissolved rock powder at tim t
Initial rock mass = Initial dry weight of applied rock powder

Solving **Equation (12)** for t_1 -t_{100}. generates 100 datapoints indicating the accumulating gross C-sink potential

All equations relating to the above SPM model and respective input parameters, are solved by an online application, processing input paramertes as enterd by the mining company, accredited laboratories, and the project owner.
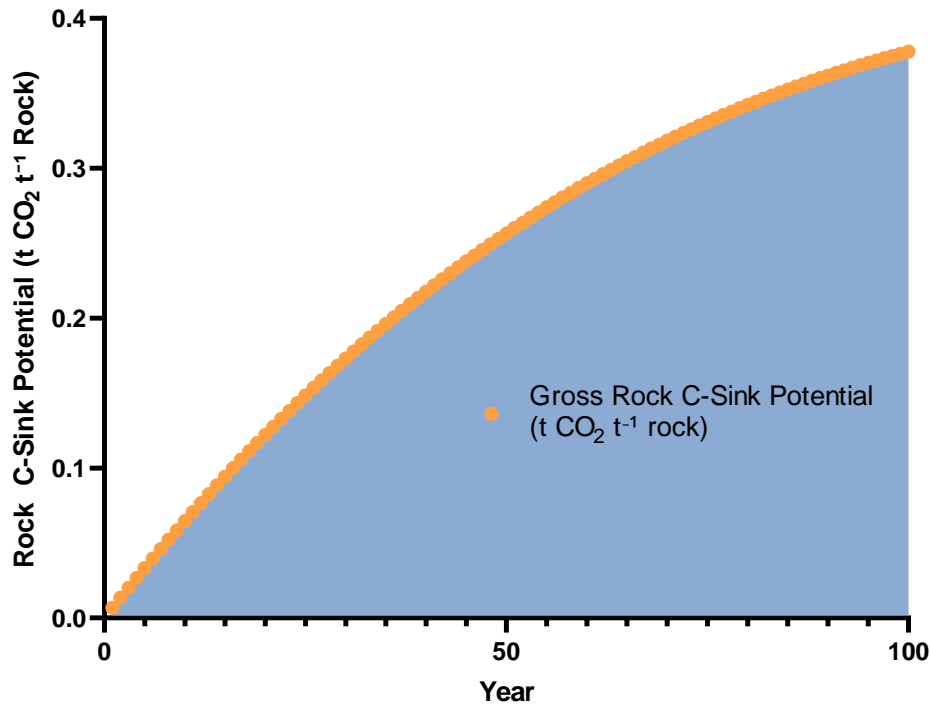
Figure 9: Expected gross C-sink curve, based on the described shrinking particle model and the following input parameters: Particle size distribution = 0-2000 µm in 8 discretely characterized fractions, 0% rock moisture, specific surface area = 1.6-2.1 m²/g, maximal carbon dioxide removal = 0.418, soil 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

In the following Chapter the gross C-sink potential will be reduced by a safety margin covering potential carbon losses, due to down stream carbonate precipitation and oceanic carbonate equilibria.

Further, the carbon expenditures of the product are quantified. Carbon expenditures are not directly deducted form the gross carbon sink, but must be seperately compensated for.

This correction and compensation measure is yielding the net C-sink potential.

5.3 Addressing uncertainties

At present, some aspects of enhanced weathering in croplands are not fully constrained, yet they are subject to ongoing research (Calabrese et al., 2022). Nevertheless, mankind is urged to implement effective climate change mitigation measures at scale as soon as possible. The present method aims to provide a first conservative calculation framework for ERW based carbon sinks. The prevailing areas of uncertainty are identified and addressed by conservative assumptions and safety margins. Therefore, the present guidelines are of highly conservative nature, likely preventing any overestimations of CDR. Below, the areas of uncertainty are summarized along with their respective counter measure.

CDR$_{max}$: Will the deployed rock powder weather completely and release all alkalinity into the soil solution, or will a fraction be permanently retained in secondary clay minerals formed as solid weathering products, or retained at other exchange sites? **Measure:** To ensure no overestimation of the CDR$_{max}$ a safety margin of 10% is deducted from the rock specific CDR$_{max}$ (Chapter 2.2.1).

In-situ **weathering rates**: How fast is a multi-mineral rock powder dissolving under specific environmental conditions? At present no modelling approach, including the present method, is validated. **Measure:** The pH and temperature dependent weathering rates (Chapter 5.1), being the basis for weathering rate scaling to field conditions, are systematically underestimated, as compared to standard atmospheric conditions[4]. Results are employed in a conservative framework. Still, the transfer of laboratory data to field conditions implies a high level of uncertainty. At present, the uncertainty regarding the weathering speed is too high, to employ Rock C-sinks for CO_2 compensation. Only a *climate service* (Global Cooling Potential) – decoupling final C-sink and temporal dynamics of C sequestration - can be valorised until the model becomes validated or replaced (see Chapter 7 Valorisation of C-sink potentials).

Soil moisture constraints: A clear and universal correlation between weathering rate and ambient soil moisture or precipitation is not yet established and remains subject to further research. **Measure:** The present method retreats to a simplified concept of *valid months* (Chapter 4.4). A valid month is defined as a month in which the soil water status is assumed sufficient, to avoid water-limitations to the reaction. Only then, the SPM is executed, otherwise weathering rates are set to 0.

Carbonate precipitation: Supersaturation and pH changes can cause the precipitation of carbonate minerals, transforming 50% of the sequestered carbon back into carbon dioxide. The occurrence of this reaction can poorly be tracked through time and space along the soil, groundwater, river water to ocean pathway. Furthermore, the persistence of the product is subject to debate. **Measure:** To ensure no overestimation, a safety margin of 10% (equivalent to the precipitation of 20% bicarbonate, forming persistent carbonate minerals) is deducted (Chapter 6.1).

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[4] The reactor liquid used in the study by Gudbrandsson et al. (2011), (see Chapter 5.1), was purged with N_2 prior to application, thus reducing dissolved CO_2 below the atmospheric equilibrium. Weathering reaction taking place herein are largely based on reactions with protons derived from water autoproteolysis, thus with reduced impact of additional carbonic acid. Calculated rates are lower than those expected under ambient CO_2 concentrations.

5.4 Outlook to alternative methods

The above method for approximating a site specific *in-situ* rock weathering rate (Chapter 5 and input variables) is deemed to serve as a pilot method, embedded in the overall guidelines for the **Certification of Carbon Sinks created by Enhanced Rock Weathering in Croplands**.

The method is based on empirical data, established modelling concepts, and embedded in a highly conservative C-sink calculation framework. However, it needs further optimization to better capture the complex realities of enhanced weathering of multi-mineral rocks in a dynamic cropland environment.

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

Advanced, process-based models in this field are "Soil Cycles of Elements simulator for Predicting Terrestrial regulation of greenhouse gases: **SCEPTER** v.0.9" by Kanzaki et al. (2022), models developed by Chipolla et al. (2021a, 2021b, 2022), and Beerling et al. (2020) and other **PhreeqC** based reactive transport models e.g., Kelland et al. (2020). Important prospects are model intercomparisons and the possible development of ensemble models (**Rock Chip Project**, Beerling et. al., *in preparation*).

Alternative approaches to future ERW carbon accounting could be based on *in-situ* reference measurement stations, spread throughout, e.g., Europe or reference experiments resembling different agroclimatic conditions. These reference stations / reference experiments may sample the liquid phase (e.g., lysimeter trials analysing soil leachates or soil extractions), the solid phase (e.g., novel empirical approach analysing soil magnesium to titanium ratios), or gaseous phase (e.g., novel empirical approach monitoring soil CO_2 concentrations). If a sufficiently representative database on possible weathering rates is compiled, reference measurement stations/ experiments may be replaced by a reference database.

Continuous measurements in each single field (and ex-post certification and credit issuance) are likely cost-prohibitive or easy to manipulate.

Data from reference stations/experiments and other *in-situ* trials should also be employed for model validation.

Future knowledge gain and novel assessment methods can be integrated in the present guidelines replacing the affected method chapters or allowing for the deployment of less conservative assumptions and safety margins.

Carbon sink potentials projected based on the present version of the guidelines will be constantly updated if the assessment method gets revised.

6 Calculation of the Rock C-Sink potential

The Rock C-Sink potential is derived according to **equation (13):**

Equation (13):

$$\text{Rock C Sink Potential} = CDR_{max} * m_{rock} * sf_{soil} * sf_{aquatic} * sf_{marine}$$

CDR_{max} = theoretical CDR capacity, including a safety factor for metals retained in clay minerals
(estimated as detailed in Chapter 2.2.1; equation 1)

m_{rock} = mass of rock powder applied per field/project in tons dry weight

sf_{soil} = safety factor of 0.9 to cover calcium carbonate precipitation
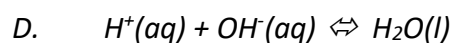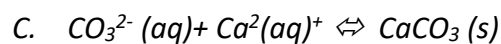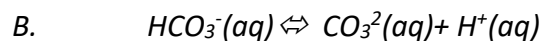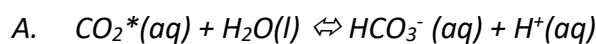(estimated as detailed in Chapter 6.1)

$sf_{aquatic}$ = safety factor of 1
(estimated as detailed in Chapter 6.1)

sf_{marine} = safety factor of 0.86, based on Lewis et al., (2021)
(estimated as detailed in chapter 6.1)

In addition, all carbon expenditures must be quantified and compensated for externally as reasoned in chapter 6.2.

6.1 Downstream losses of dissolved inorganic carbon

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

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 pH determines, the relative partitioning of the three species within the total dissolved inorganic carbon (Fig. 10).

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Approval date:06.04.2023 15:04:33

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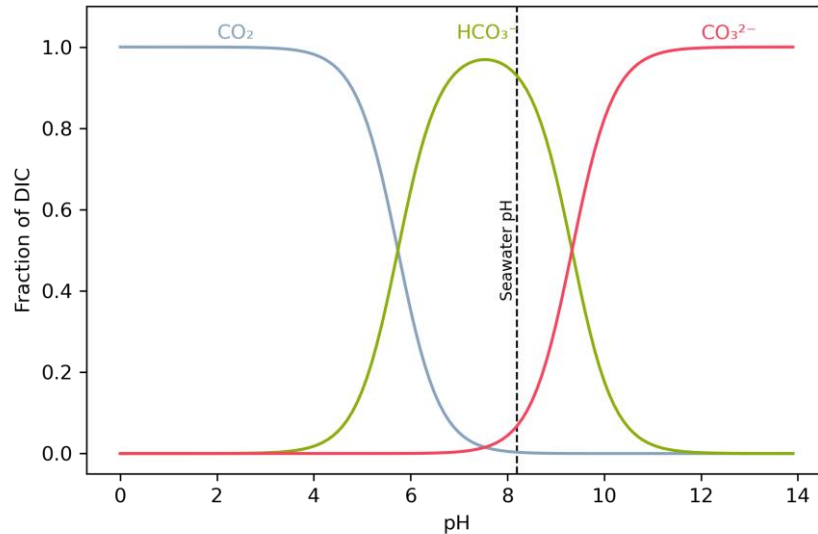
Figure 10: The pH dependent equilibria of dissolved inorganic carbon species. Considering common pH ranges of ground- river or ocean water, the largest share of dissolved inorganic carbon will be present as bicarbonate. Bicarbonate can no longer directly exchange with the atmosphere.

The interactions in this system are complex and depend on many factors, including pH, alkalinity, ionic strength, exchange of CO_2 with the atmosphere, uptake of CO_2 via primary production, and input of CO_2 via, e.g., decomposition of organic matter. When $CaCO_3$ precipitates (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, neither of the following, commonly used equations fully depict underlying chemistry:

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

$$Ca^{2+} (aq) + CO_3^{2-} (aq) \rightarrow CaCO_3 (s)$$
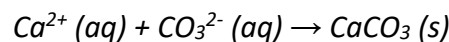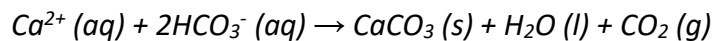
Thus, we evaluate the likeliness of carbonate precipitation in soil pore water, groundwater, rivers, and the ocean (Fig.11).
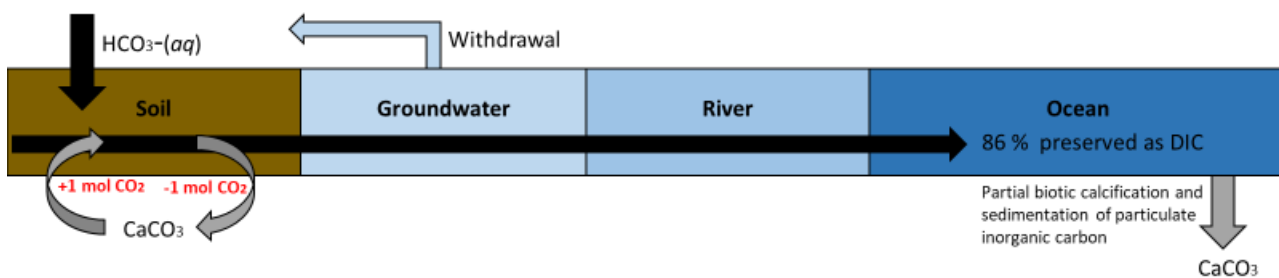
Figure 11: Schematic pathway of HCO_3^--(aq) from field to ocean. Considering soil solution, ground- and river water chemistry, substantial precipitation pf persistent calcium carbonate is neglectable.

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 3.1.1 decadal aridity index and Chapter 4.3 soil moisture and *valid month* nominator). 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 that of the model silicate rock being tracked for 100 years. (Arvidson et al, 2003).

Groundwater

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

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.

Riverine transport

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 is the dominating bicarbonate 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 sub-chapter "Riverine transport" 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. For now, potential losses are covered by safety factors as described below.

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). 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.

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.

Safety factors addressing the downstream losses of DIC

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). A 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. Substantial losses from groundwater and riverine systems are not expected ($M_{aquatic}$ = 1). A further multiplication with 0.86 corrects for the midterm CDR efficiency, i.e., losses through the equilibrating oceanic carbonate systems (M_{marine} = 0.86).

To illustrate the expected C-sink curve, also the 100 data points generated by the MSP model must be corrected accordingly (Fig.12).
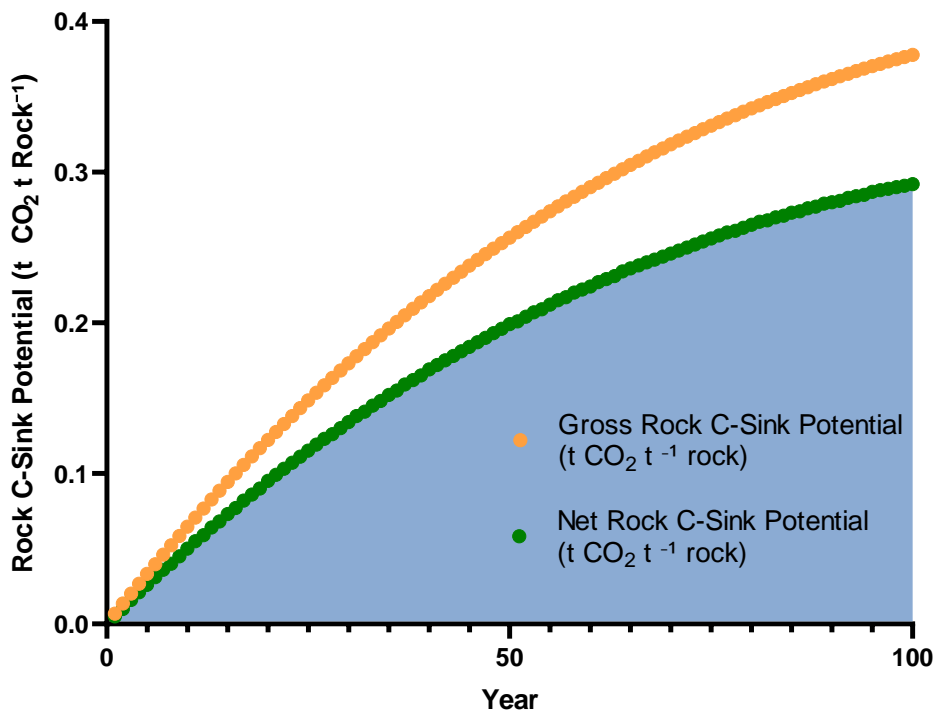
Figure 12: Expected net C-sink curve based on the described shrinking particle model and the following input parameters: Particle size distribution = 0-2000 µm in 8 discretely characterized fractions, 0% rock moisture, specific surface area = 1.6-2 m²/g, maximum carbon dioxide removal = 0.418, soil pH = 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.

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

6.2 Carbon expenditures

The rock powder value chain is requiring substantial energy inputs from mine to field. This includes, e.g., energy used for mining operations, rock milling, road- railroad- or naval- transportation of the rock powder and field application of the latter using tractors.

Energy and materials used along the value chain are causing direct and indirect greenhouse gas emissions in the form of CO_2. In the context of C-sink potential certification, such emissions are called *carbon expenditures*. All carbon expenditures must be compensated for, by the retirement of an equivalent C-sink (compensation). This way, only real net negative, emissions will be certified as carbon sinks. Operations emitting more - or only slightly less -CO_2 than they are sequestering are rendered uneconomic and fail to enter the carbon market.

The adequate attribution of emissions to the C-sink is important. The present guidelines will address the issue of emission attribution, by distinguishing between two rock powder sources: 1. Rock powder from **mine tailings** (unintentionally produced rock powder, originating as a by-product from other mining operations which already took place in the baseline scenario) and 2. **rock powder exclusively produced for ERW purposes** (representing an additionality to the baseline production of the company i.e. not being a waste product of the business as usual scenario).

Emission attribution to mine tailings:

For a transition period of 3 years past the publication of this guideline, 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. If this is made plausible, the carbon expenditures per ton of rock powder must only cover emissions originating from material transport (factory gate to field) and emissions originating from rock powder field applications (diesel usage by farm machinery).

Past this transition period, mine tailings must additionally be attributed with a share of the scope 1 – scope 3 emissions as described in Chapter 8.1.2. The share of attributable emissions is equivalent to the share of annual revenue generated from rock powder sale, from the total annual revenue generated from the mining activities. (e.g., if 5% of the revenue is generated from sale of rock powder, 5% of the companies scope 1 – scope 3 emissions must be attributed to the rock powder production).; thus, no emissions will be attributed in the first year. This is based on practical considerations and is also intended to facilitate entry into ERW.

Emission attribution to rock powder exclusively produced for ERW purpose:

Carbon expenditures per ton of rock powder must cover 100% of the emissions originating from mining and milling operations relating to the rock powders production (see chapter 8.1.2), material transport (factory gate to field) and emissions originating from rock powder field applications (diesel usage of farm machinery)

Carbon expenditures are expressed in the unit t CO_2e t rock powder^{-1}.

Carbon expenditures per t rock powder can be calculated as the ratio of annual emissions to annual rock powder production, also here data of the past year will be used.

The mining company specific carbon expenditures are verified by the certification body q.inspecta AG.

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

The sum of the production- (mining and milling) and field specific (transport and application) carbon expenditures must be compensated through the retirement of an equivalent C-sink before the associated Rock C-sink potential or Rock C-sink curve can be entered in a carbon registry and is admitted for sale as a climate service or CO_2 emission compensation

7 Valorisation of carbon sink potentials

While persistence is assured by the nature of Rock C-sinks, the timing of the negative emission (i.e., the time when the CO_2-extraction from the atmosphere occurs) requires further attention and assessment schemes remain subject to validation. While it can be assumed that most of the rock minerals applied to admissible land-units (see Chapter 3) will have weathered after a period of 70-100 years, the timing of the C sequestration cannot yet be determined with sufficient accuracy.

- Before models or other Rock C-sink assessment methods are validated the present guidelines suggest the certification of the **Rock C-sink potential**, based on documented and certified rock powder applications **(as detailed in Chapter 6.1 and 7.1).** The Rock C-sink potential certifies the final C-sink, decoupled from the temporal dynamics of its C-sink curve. Such assets can be valorised as a **climate service**, i.e., the creation of a C-sink outside of the CO_2 compensation market.

- Once models or other CDR assessment methods are validated, and thus the temporal dynamics of Rock C-sink curves are known with sufficient certainty and precision, the present guidelines will allow for the employment of **Rock C-sink potentials for CO_2-emission compensations when use as part of C-sink portfolios (Chapter 7.2)**.

7.1 Rock C-Sink potentials as a climate service

Based on certified rock powder applications (including rock powder characterization, field characterization and documentation of the application) The Rock C-sink potential of an ERW project can be certified.

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 C-sink curve. It is calculated as per Chapter 6.1. Such Rock C-sink potentials can be traded as a climate service. A climate service describes the creation of a C-sink within a time horizon relevant to mitigate anthropogenic climate change. It is evident, that the CDR occurs and that it reaches the certified potential nevertheless, it is not yet known with sufficient precision what size the C-sink reaches at any given moment between the application and year 100. The latter would be necessary to create C-sink portfolios for the compensation of CO_2-emissions (Chapter 7.2).

This present certification scheme allows for the certification of a significant, long-term global cooling effect due to CDR and fosters immediate and vital climate mitigation activities. It paves the way for the creation of a market for climate mitigation services (C-sink creation) decoupled from the CO_2 compensation market.

CO_2 compensations may serve the purpose of reaching net zero emissions targets; however, the removal of legacy emissions remains as a separate challenge as important as emission reduction and compensation. The IPCC calculates that 800 Gt of CO_2 must be removed from the atmosphere until 2100, to reach the Paris climate targets as per the shared socioeconomic pathway 2 and the representative concentration pathway 1.9 (SSP2 RCP1.9). This removal must be realized beside the compensation of remaining GHG-emissions (IPCC, 2018).

The expected C-sink curve and considerations regarding the persistence of Rock C-sinks (comparable to direct air capture + underground, mineral carbon storage) may serve as orientation for the pricing of this climate service.

Also, climate services may be aggregated in C-sink portfolios (Chapter 7.2), here the guidelines advise the C-sink trader to make transparent the uncertainties about the temporal dynamics. The trader has further to state that these climate services cannot be employed for CO_2 compensation.

7.2 Carbon sink portfolios

Once the expected C-sink curve is validated for a time horizon of 100 years past application, Rock C-sinks may also be employed for CO_2 emission compensations. However, this is only possible when used as part of a C-sink portfolio.

Controlled by environmental factors, Rock C-sinks build up over a time horizon of decades to centuries, with the ocean being the final sink of sequestered atmospheric carbon. Rock-C-sinks are characterized by the fact that the longer the considered time horizon, the lower the uncertainty and, the higher the likelihood that DIC is formed and that it reached the ocean.

Employing a C-sink for CO_2 emission compensation, whose potential will only be established in the future, requires a sensible approach to using and trading those C-sinks. Timing is an important factor in the evaluation of negative emissions: Every ton of CO_2 removed from the atmosphere today mitigates today's climate, while a later removal will delay the desired effect. Also, to compensate the global warming effect of CO_2-emissions that occurred in the past or do so today, the negative emission (removing CO_2 from the atmosphere) must be realised now to avoid climate warming and its accelerating feedback loops.

To be applicable as compensation for a CO_2-emission, the persistence of an equally (100%) sized C-sink (based on an CO_2e calculation) must be guaranteed for at least 100 years. This is called the ***100% 100year*** principle of CO_2-compensation.

Different C-sinks show different temporal dynamics. While Rock-C-sinks build up over time, others may predictably degrade, such as the labile fraction of biochar. Few C-sinks can be assumed to be constant over a relevant period (e.g., >100 years), such as the persistent fraction of biochar C or geological stored CO_2. Others are subject to discrete or only partially predictable dynamics that require repeated measurements and/or monitoring, such as forest or biomass uses (e.g., wood construction). Since global warming depends on the total amount of greenhouse gases in the atmosphere, which is directly linked to the amount of carbon stored outside the atmosphere (C-sinks) at any given moment in time, a summary tool is defined that maps these C-sink dynamics in a uniform way:

> A <u>C-sink portfolio</u> is defined as the arithmetic combination of the C-sink curves of C-sinks with different time horizons, at different locations, and/or using different negative emission technologies.

To compensate a CO_2-emission, an equally sized C-sink must be retired (no resale possible) for at least 100 years. The C-sink for CO_2-emission compensation must be of constant size at each moment during the minimum compensation period of 100 years (100% 100y). A C-sink can consist of several individual C-sinks with different time horizons grouped in a C-sink portfolio (see Fig. 13 and 14).

> A <u>C-sink curve</u> is defined as the function that delivers the amount of carbon stored in a C sink, expressed in tons of C or tons of CO_2e, at any given point in time.

To facilitate the application of C-sink curves in C-sink portfolios, they are presented in discrete 5-year segments, each representing the average amount of carbon stored during those 5-year periods.

Thus, a C-sink portfolio is an assessment and trading tool that combines C-sink curves originating from different types of carbon sinks. It enables the valorisation of increasing and decreasing, long- and short-term C-sinks and their use to obtain carbon removal of a uniform quality to compensate CO_2 emissions.

The constant C-sinks and C-sink curves add to each other in 20 defined 5-years segments over 100 years (e.g., the C-sink value of the first 5 years of biochar applied to a given soil and the C-sink value of the first 5 years of Rock C-sink in a given soil sum up to the C-sink portfolio value over the time horizon of those 5 years).

The same is repeated for every 5-year period until the time horizon of 100 years is reached. The C-sink portfolio is, thus, built up over the defined 100 years period following the application of the C-sink material (e.g., biochar, ERW-minerals) to the C-sink (e.g., soil).

The portfolio C-sink presents the time-dependent total C-sink of all included C-sinks. However, only the portion of the portfolio C-sink that presents the same C-sink value in each of the 20 five-years periods (100% 100y) can be used (sold) for CO_2-emission compensation (see Figure 12 and 13). Proportions of a 5-year C-sink segment overshooting the desired CO_2e-compensation area of the portfolio can be cut-off and used in a different portfolio.

Following the above principles, Rock-C-sinks can be included in C-sink portfolios. Based on a portfolio, C-sink certificates of unprecedented rigor granting an immediate, constant, and persistent carbon removal from year 1 until year 100 are generated.
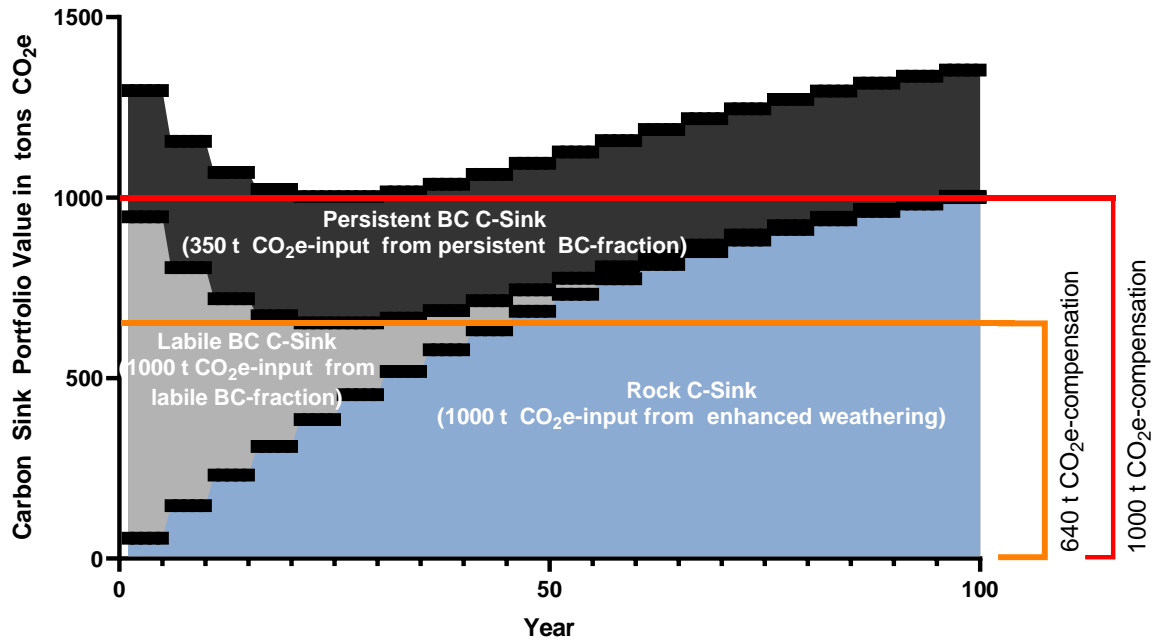
Figure 13: *A carbon sink portfolio of enhanced rock weathering and biochar-based carbon sinks permitting to compensate a GHG-emission of 1000 t CO_2e (100% 100 years). It is compiled from the 5-year segments of 3 different C-sink curves, namely a 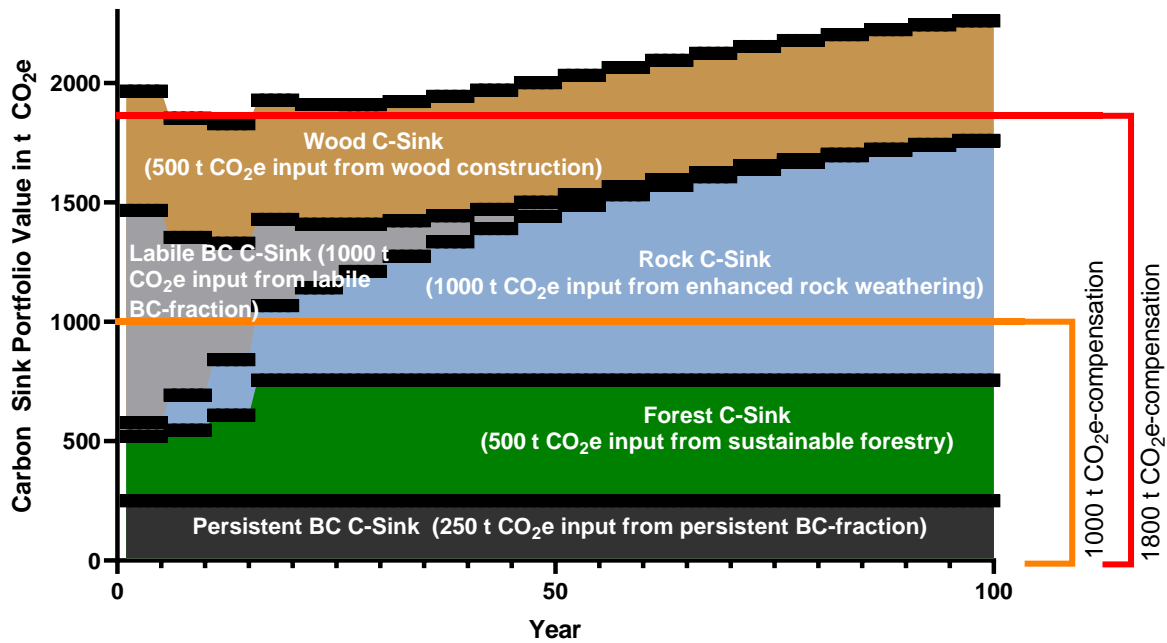Rock C-Sin k(blue), a persistent biochar-based C-Sink (black), and a labile biochar-based C-Sink (grey). If only the Rock C-sink and the labile biochar pool are used, an emission of 640 t CO_2e can be compensated. BC= Biochar; CO_2e = CO_2 equivalents.*

*The red block is a C-sink portfolio of 1000 t CO_2e with a minimum persistence of 100 years. It consists of **(1)** an increasing Rock C-Sink that reaches 1000 t CO_2e after 100 years, **(2)** the labile fraction of a biochar C-Sink that held 1000 t CO_2e at the beginning (year 0) and decreases exponentially to 0 t CO_2e at the end of the 100 year period, and **(3)** a persistent biochar C-Sink of 350 t CO_2e that was applied to soil at the beginning (year 0) and maintains its entire C-sink over the 100 years. All three C-sinks added together result in a C-sink that never falls below the limit of 1000 t CO_2e during the first 100 years and can be used to compensate 1000 t CO_2e emissions. Proportions of a 5-year C-sink segment overshooting the red block of the portfolio can be cut-off and deployed in a different portfolio.*

*The orange block indicates an alternative C-sink (climate service or emission compensation product that could be sold), which could be derived from the same portfolio. The orange block envelopes a C-Sink of 640 t CO_2e with a minimum persistence of 100 years. It consists of **(1)** an increasing Rock C-Sink that reaches 1000 t CO_2e after 100 years and **(2)** the labile fraction of a Biochar C-Sink that was 1000 t CO_2e at the beginning (year 0) and decreases exponentially to 0 t CO2e at the end of the 100-year period. The two C-sinks added together result in a C-sink that never falls below the limit of 640 t CO_2e during the first 100 years and can be used to compensate 640 t CO_2e emissions. Proportions of a 5-year C-sink segment overshooting the orange block of the portfolio can be cut-off and deployed in a different portfolio.*

The same principle can be applied for portfolios of different sizes and complexity, customizing different portfolios and CO_2e compensations.

Figure 14: *A diversified carbon sink portfolio equivalent to 1800 t CO_2e (100% 100 years). It is compiled from the 5-year integrals of 5 different C-sink curves, namely a Rock C-Sink (blue), a persistent biochar-based C-Sink (black), a labile biochar-based C-Sink (grey), a forest C-Sink (green) and a C-Sink originating from wood construction (brown). The compiled 5-year segments add up to a C-Sink portfolio (100% 100 years) that allows for the compensation of 1800 t CO_2e. BC= Biochar; CO_2e = CO_2 equivalents.*

*The red block is a C-sink of 1800 t CO_2e with a minimum persistence of 100 years. It consists of **(1)** a persistent biochar C-Sink of 250 t CO_2e that was applied to soil at the beginning (year 0) and maintains its C-sink equal over the entire 100 years, **(2)** an increasing forest C-Sink that reaches its equilibrium after 20 years, **(3)** an increasing Rock C-Sink that reaches 1000 t CO_2e after 100 years, **(4)** the labile fraction of a biochar C-Sink that was 1000 t CO_2e at the beginning (year 0) and decreases exponentially to 0 t CO_2e at the end of the 100 years period, and **(5)** a constant 500 t CO_2e wood C-Sink originating from wood construction. All five C-sinks added together result in a persistent c-sink that never falls below the limit of 1800 t CO_2e and can be used to compensate 1800 t CO_2e emissions. Proportions of a 5-year C-sink segment overshooting the red block of the portfolio can be cut-off and deployed in a different portfolio.*

*The orange block indicates an alternative C-sink (climate service or emission compensation product that could be sold), which can be derived from the same portfolio. The orange block envelopes a C-Sink of 1000 t CO_2e with a minimum persistence of 100 years. It consists of **(1)** a persistent biochar C-Sink of 250 t CO_2e that was applied to soil at the beginning (year 0) and maintains its C-sink equal over the entire 100 years, **(2)** an increasing forest C-Sink, that reaches its equilibrium after 20 years, **(3)** an increasing Rock C-Sink that reaches 1000 t CO_2e after 100 years and **(4)** the labile fraction of a biochar C-Sink that was 1000 t CO_2e at the beginning (year 0) and decreases exponentially to 0 t CO_2e at the end of the 100 year period. The four C-sinks added together result in a persistent c-sink that never falls below the limit of 1000 t CO_2e and can be used to compensate 1000 t CO_2e emissions. Proportions of a 5-year C-sink segment overshooting the orange block of the portfolio can be cut-off and deployed in a different portfolio.*

8 Certification

8.1 Rock powder product certification

The certification of the mining company and rock powder product is carried out by the certification body. The responsible certification body q.inspecta GmbH is approved by Carbon Standards International and accredited by the Swiss Accreditation Service SAS. During an on-site visit, all requirements and data regarding environmental protection, work safety, process emissions and rock powder sampling are controlled.

8.1.1 Basic requirements for the company

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.

Health and Work Safety

Fire and dust protection regulations have to 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.

8.1.2 Emission factors

Product specific emission factors as described below must to be identified and updated once a year by the certifier to warrant adequate consideration of carbon expenditures.

To calculate the carbon expenditures originating from scope 1 and scope 2[5] 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.
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 **(14)** as follows:

Equation (14):

$$Ex_{production} = \left(\left(E_{mining+} E_{milling} \right) * EF + \left(F_{mining} + F_{milling} \right) * 0.0032\ t\ CO_2 e \right) * 1.11$$

***Ex*_{production}** *= emission factor in t CO$_2$e t^{-1} rock powder.*
E *= energy usage in MWh t rock^{-1}*
EF *= national emission factor for the electricity generation in t CO$_2$e MWh^{-1}.*
F *= fuels (diesel) usage in L*
0.0032 t CO$_2$e *= mean CO$_2$e emission from burning 1 L diesel (Juhrich, 2016)*
***1.1 =** margin to incorporate scope 3 emissions.*

For a pilot phase, defined as 2022- 2023, emission factors as declared by the company will be accepted. On-site inspection and verification become mandatory from January 1st .2024 onwards.

A revision of company and product specific emission factors must take place at least every 12 months and after a change in deployed mining and/or milling technologies.

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

Downstream emissions resulting from transportation must be calculated based on transport distance according to **Equation (15).**

Equation (15):

---

[5] 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.

$$Ex_{transport} = distance * 0.000113 \; t \; CO_2e \; km^{-1}$$

$Ex_{transport}$= 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.

For the field application a conservative estimate of 0.004 t CO_2 per ton rock powder (Moosdorf et al., 2014) applies.

The total carbon expenditures t^{-1} rock powder are calculated according to **Equation (16).**

Equation (16):

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

CE = Carbon expenditures t CO_2e t^{-1} rock powder.
$Ex_{production}$ = emission factor in t CO_2e t^{-1} rock powder.
$Ex_{transport}$= Transport emissions in t CO_2 t^{-1} rock powder
$Ex_{application}$= Application emissions in t CO_2 t^{-1} rock powder

The field or project specific carbon expenditures are the product of the carbon expenditures per ton rock powder and the number of tons rock powder applied.

8.1.3 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 unique 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 6 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 and is carried out by a laboratory accredited through Carbon Standards International. The accredited laboratories are listed on the website of Carbon Standards International.

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.

8.1.4 Delivery unit ID

Before a delivery can happen, the batches have to be certified. Each ton of rock powder ordered and applied by a farmer or other project owner must be associated to a unique delivery-unit ID. All delivery-unit IDs must be associated to a certified batch ID (see chapter 8.1.3). The delivery unit IDs and associated rock powder quantities must be accessible for the certification body.

The delivery note issued by the mining company or distributor must indicate the batch ID and delivery-unit ID both in plain text and a forgery proofed QR code. The QR code is further linking to a viewable online database where the rock characterisation according to Annex 10.1.1 and field characterizations can be consulted.

The farmer or project owner must upload an image of the delivery note along with a geo-tagged image of the unloaded rock powder to the provided online registry system. This links the delivery to the certified batch.

8.2 Certification of the Rock C-Sink potential

For successful certification of a batch all required data must be compiled in the provided online tools and approved by the certification body.

The project owner must provide farm and field specific data to the online tools which includes:

- Farmers name and address
- Field size
- Field GPS-coordinates (Point Coordinate + KML Polygon)
- Application date
- Application amount (t field^{-1})
- Delivery unit and Batch-ID
- Delivery Note and geo-tagged picture

- Soil parameters (Annex 10.1.2)
- Agroclimatic parameters of the region (Chapter 4)

A field is defined as connected land unit being subject to identical land management and having a maximum size of 10 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 project owner 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.

Until model validation or replacement, the C-sink curve is only indicative, but not certified. As per version 1.0 of the present guidelines, only the Rock C-sink potential will be certified and admitted for sale as a climate service as per chapter 7.1.

8.2.1 Geographic validity range

Any ERW-projects outside the European Union must send an application to Carbon Standards International to open a dossier for the addition of a country specific Annex document, addressing the ERW applications in the face of applicable national legislation and assessing the quality of available agroclimatic data (Annex 10.2).

8.2.2 Accreditation of carbon-sink traders

A C-sink trader is an entity coordinating and managing the trade and registry of carbon sinks and C-sink potentials as part of C-sink portfolios.

To be eligible under the present guidelines a carbon trader must be accredited by Carbon Standards International.

C-sink traders can also execute monitoring tasks, targeting the downstream carbon expenditures (past factory gate emissions, e.g., transport emissions) if suitable infrastructure is present. The respective tracking systems must be approved by Carbon Standards International.

9 References

Akter, M., & Akagi, T. (2005). Effect of fine root contact on plant-induced weathering of basalt. Soil Science & Plant Nutrition, 51(6), 861-871.

Akter, M., & Akagi, T. (2010). Dependence of plant-induced weathering of basalt and andesite on nutrient conditions. Geochemical Journal, 44(2), 137-150.

Amann, T., & Hartmann, J. (2019). Ideas and perspectives: Synergies from co-deployment of negative emission technologies. Biogeosciences, 16(15), 2949-2960.

Amann, T., & Hartmann, J. (2022). Carbon Accounting for Enhanced Weathering. Frontiers in Climate, 54.

Amann, T., Hartmann, J., Hellmann, R., Pedrosa, E. T., & Malik, A. Enhanced Weathering potentials-the role of in situ CO_2 and grain size distribution. Frontiers in Climate, 131.

Arvidson, R. S., Ertan, I. E., Amonette, J. E., & Luttge, A. (2003). Variation in calcite dissolution rates: A fundamental problem? Geochimica et cosmochimica acta, 67(9), 1623-1634.

Bai, Y., & Cotrufo, M. F. (2022). Grassland soil carbon sequestration: Current understanding, challenges, and solutions. Science, 377(6606), 603-608.

BbodSchG (1998) Gesetz zum Schutz vor schädlichen Bodenveränderungen und zur Sanierung von Altlasten (Deutsches Bundes-Bodenschutzgesetz – BbodSchG). Last Revision 2021

Beerling, D. J., Kantzas, E. P., Lomas, M. R., Wade, P., Eufrasio, R. M., Renforth, P. & Banwart, S. A. (2020). Potential for large-scale CO_2 removal via enhanced rock weathering with croplands. Nature, 583(7815), 242-248.

Bide, T. P., Styles, M. T., & Naden, J. (2014). An assessment of global resources of rocks as suitable raw materials for carbon capture and storage by mineralisation. Applied Earth Science, 123(3), 179-195.

BMU (2008) Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz: Grundwasser in Deutschland
BGR (2016) Bundesanstalt für Geowissenschaften und Rohstoffe: Die Grundwasservorkommen von Deutschland (online 10.09.2022)
Buss, H. L., Lüttge, A., & Brantley, S. L. (2007). Etch pit formation on iron silicate surfaces during siderophore-promoted dissolution. Chemical Geology, 240(3-4), 326-342

Calabrese, S., Wild, B., Bertagni, M., Bourg, I., White, C., Aburto, F., Chipolla, G., Noto, L., & Porporato, A. (2022) Nano- to global-scale uncertainties in terrestrial enhanced weathering. Environmental Science & Technology.

Campbell, J. S., Foteinis, S., Furey, V., Hawrot, O., Pike, D., Aeschlimann, S., ... & Renforth, P. (2022). Geochemical Negative Emissions Technologies: Part I. Review. Frontiers in Climate, 4, 879133.

Cipolla, G., Calabrese, S., Noto, L. V., and Porporato, A.: The role of hydrology on enhanced weathering for carbon sequestration I. Modeling rock-dissolution reactions coupled to plant, soil moisture, and carbon dynamics, Advances in Water Resources, 154, 103 934.

Cipolla, G., Calabrese, S., Noto, L. V., and Porporato, A.: The role of hydrology on enhanced weathering for carbon sequestration I. Modeling rock-dissolution reactions coupled to plant, soil moisture, and carbon dynamics, Advances in Water Resources, 154, 103 934.

Cipolla, G., Calabrese, S., Porporato, A., & Noto, L. (2022). Effects of precipitation seasonality, vegetation cycle, and irrigation on enhanced weathering. EGUsphere, 1-29.

Davidson, E. A., & Trumbore, S. E. (1995). Gas diffusivity and production of CO_2 in deep soils of the eastern Amazon. Tellus B: Chemical and Physical Meteorology, 47(5), 550-565.

De Oliveira Garcia, W., Amann, T., Hartmann, J., Karstens, K., Popp, A., Boysen, L. R. & Goll, D. (2020). Impacts of enhanced weathering on biomass production for negative emission technologies and soil hydrology. Biogeosciences, 17(7), 2107-2133.

Deng, H., Poonoosamy, J., & Molins, S. (2022). A reactive transport Modelling perspective on the dynamics of interface-coupled dissolution-precipitation. Applied Geochemistry, 137, 105207.

Drever, J. I. (1988). The geochemistry of natural waters (Vol. 437). Englewood Cliffs: Prentice hall. DüMV (2012) Verordnung über das Inverkehrbringen von Düngemitteln, Bodenhilfsstoffen, Kultursubstraten und Pflanzenhilfsmitteln (Deutsche Düngemittelverordnung - DüMV). Last Revision: 2017

DüV (2017) Verordnung über die Anwendung von Düngemitteln, Bodenhilfsstoffen, Kultursubstraten und Pflanzenhilfsmitteln nach den Grundsätzen der guten fachlichen Praxis beim Düngen (Deutsche Düngeverordnung – DüV). Last Revision 2021

DWD (2022) Deutscher Wetterdienst. Online
https://www.dwd.de/EN/ourservices/cdc/cdc_ueberblick-klimadaten_en.html

EASAC (2018) Negative emission technologies: What role in meeting Paris Agreement targets? European Academies Science Advisory Council. Policy reports 35. ISBN: 978-3-8047-3841-6

EU (2019). Verordnung (EU) 2019/1009 des Europäischen Parlaments und europäischen Rates mit Vorschriften für die Bereitstellung von EU-Düngeprodukten auf dem Markt und zur Änderung der Verordnungen (EG) Nr. 1069/2009 und (EG) Nr. 1107/2009 sowie zur Aufhebung der Verordnung (EG) Nr. 2003/2003.

Gislason, S. R., & Oelkers, E. H. (2003). Mechanism, rates, and consequences of basaltic glass dissolution: II. An experimental study of the dissolution rates of basaltic glass as a function of pH and temperature. Geochimica et Cosmochimica Acta, 67(20), 3817-3832.

Goldich, S. S. (1938) A study in rock-weathering, Journal of Geology, 46(1), 17–58.

Gudbrandsson, S., Wolff-Boenisch, D., Gislason, S. R., & Oelkers, E. H. (2011). An experimental study of crystalline basalt dissolution from $2 \leqslant pH \leqslant 11$ and temperatures from 5 to 75 C. Geochimica et Cosmochimica Acta, 75(19), 5496-5509.

Hangx, S. J., & Spiers, C. J. (2009). Coastal spreading of olivine to control atmospheric CO_2 concentrations: A critical analysis of viability. International Journal of Greenhouse Gas Control, 3(6), 757-767.

Haque, F., Santos, R. M., & Chiang, Y. W. (2020). Optimizing inorganic carbon sequestration and crop yield with wollastonite soil amendment in a microplot study. Frontiers in plant science, 11, 1012. Haque, F., Santos, R. M., Dutta, A., Thimmanagari, M., & Chiang, Y. W. (2019). Co-benefits of wollastonite weathering in agriculture: CO_2 sequestration and promoted plant growth. ACS omega, 4(1), 1425-1433.

Hartmann, J., West, A. J., Renforth, P., Köhler, P., De La Rocha, C. L., Wolf-Gladrow, D. A., & Scheffran, J. (2013). Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. Reviews of Geophysics, 51(2), 113-149.

IPCC (2018) Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 93-174.

Juhrich, K. (2016). CO_2-Emissionsfaktoren für fossile Brennstoffe. Berlin.

Kanzaki, Y., Zhang, S., Planavsky, N. J., & Reinhard, C. T. (2022). Soil Cycles of Elements simulator for Predicting TERrestrial regulation of greenhouse gases: SCEPTER v0. 9. Geoscientific Model Development Discussions, 1-58.

Kelland, M. E., Wade, P. W., Lewis, A. L., Taylor, L. L., Sarkar, B., Andrews, M. G.,Beerling, D. J. (2020). Increased yield and CO2 sequestration potential with the C4 cereal Sorghum bicolor cultivated in basaltic rock dust-amended agricultural soil. Global Change Biology, 26(6), 3658-3676.

Köhler, P., Hartmann, J., & Wolf-Gladrow, D. A. (2010). Geoengineering potential of artificially enhanced silicate weathering of olivine. Proceedings of the National Academy of Sciences, 107(47), 20228-20233.

Krahl, L. L. (2020). Mineral formation and element release from aluminosilicate rocks promoted by maize rhizosphere.

Lewis, A. L., Sarkar, B., Wade, P., Kemp, S. J., Hodson, M. E., Taylor, L. L., & Beerling, D. J. (2021). Effects of mineralogy, chemistry and physical properties of basalts on carbon capture potential and plant-nutrient element release via enhanced weathering. Applied Geochemistry, 132, 105023.

Liermann, L. J., Kalinowski, B. E., Brantley, S. L., & Ferry, J. G. (2000). Role of bacterial siderophores in dissolution of hornblende. Geochimica et Cosmochimica Acta, 64(4), 587-602.

Monasterio-Guillot, L., Rodriguez-Navarro, C., & Ruiz-Agudo, E. (2021). Kinetics and Mechanisms of Acid-pH Weathering of Pyroxenes. Geochemistry, Geophysics, Geosystems, 22(11)

Moosdorf, N., Renforth, P., & Hartmann, J. (2014). Carbon dioxide efficiency of terrestrial enhanced weathering. Environmental Science & Technology, 48(9), 4809-4816.

Morris, J. P., & Humphreys, M. P. (2019). Modelling seawater carbonate chemistry in shellfish aquaculture regions: Insights into CO2 release associated with shell formation and growth. Aquaculture, 501, 338-344.

Navarre-Sitchler, A., & Brantley, S. (2007). Basalt weathering across scales. Earth and Planetary Science Letters, 261(1-2), 321-334.

NRCCA (2022). Northeast Region Certified Crop Adviser (NRCCA) Study Resources. Cornell university. Online: nrcca.cals.cornell.edu/soil/CA2/CA0212.1-3.php

Parkhurst, D. L., & Appelo, C. A. J. (1999). User's guide to PHREEQC (Version 2): A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. Water-resources investigations report, 99(4259), 312.

Quirk, J., Andrews, M. Y., Leake, J. R., Banwart, S. A., & Beerling, D. J. (2014). Ectomycorrhizal fungi and past high CO2 atmospheres enhance mineral weathering through increased below-ground carbon-energy fluxes. Biology letters, 10(7), 20140375.

Quirk, J., Beerling, D. J., Banwart, S. A., Kakonyi, G., Romero-Gonzalez, M. E., & Leake, J. R. (2012). Evolution of trees and mycorrhizal fungi intensifies silicate mineral weathering. Biology letters, 8(6), 1006-1011.

Renforth, P. (2012). The potential of enhanced weathering in the UK. International Journal of Greenhouse Gas Control, 10, 229-243.

Renforth, P., & Campbell, J. S. (2021). The role of soils in the regulation of ocean acidification. Philosophical Transactions of the Royal Society B, 376(1834), 20200174.

Renforth, P., & Henderson, G. (2017). Assessing ocean alkalinity for carbon sequestration. Reviews of Geophysics, 55(3), 636-674.

Renforth, P., von Strandmann, P. P., & Henderson, G. M. (2015). The dissolution of olivine added to soil: Implications for enhanced weathering. Applied Geochemistry, 61, 109-118.

Rinder, T., & von Hagke, C. (2021). The influence of particle size on the potential of enhanced basalt weathering for carbon dioxide removal-Insights from a regional assessment. Journal of Cleaner Production, 315, 128178.

Schott, J., Pokrovsky, O. S., & Oelkers, E. H. (2018). 6. The Link Between Mineral Dissolution/Precipitation Kinetics and Solution Chemistry. In Thermodynamics and Kinetics of Water-Rock Interaction (pp. 207-258). De Gruyter.

Stockmann, G. J., Wolff-Boenisch, D., Gislason, S. R., & Oelkers, E. H. (2013). Do carbonate precipitates affect dissolution kinetics? 2: Diopside. Chemical Geology, 337, 56-66.

Stockmann, G. J., Wolff-Boenisch, D., Gislason, S. R., & Oelkers, E. H. (2011). Do carbonate precipitates affect dissolution kinetics? 1: Basaltic glass. Chemical Geology, 284(3-4), 306-316.

Strefler, J., Amann, T., Bauer, N., Kriegler, E., & Hartmann, J. (2018). Potential and costs of carbon dioxide removal by enhanced weathering of rocks. Environmental Research Letters, 13(3), 034010.

Tester, J. W., Worley, W. G., Robinson, B. A., Grigsby, C. O., & Feerer, J. L. (1994). Correlating quartz dissolution kinetics in pure water from 25 to 625 C. Geochimica et Cosmochimica Acta, 58(11), 2407-2420.

Torres, M. A., Dong, S., Nealson, K. H., & West, A. J. (2019). The kinetics of siderophore-mediated olivine dissolution. Geobiology, 17(4), 401-416.

UBA (2022) Emissionsdaten Verkehr. Online: www.umweltbundesamt.de/themen/verkehr-laerm/emissionsdaten

Upadhyay, S., Singh, R., Verma, P., & Raghubanshi, A. S. (2021). Spatio-temporal variability in soil CO_2 efflux and regulatory physicochemical parameters from the tropical urban natural and anthropogenic land use classes. Journal of Environmental Management, 295, 113-141.

Verbruggen, E., Struyf, E., & Vicca, S. (2021). Can arbuscular mycorrhizal fungi speed up carbon sequestration by enhanced weathering? Plants, People, Planet, 3(5), 445-453.

Vicca, S., Goll, D. S., Hagens, M., Hartmann, J., Janssens, I. A., Neubeck, A., & Verbruggen, E. (2022). Is the climate change mitigation effect of enhanced silicate weathering governed by biological processes? Global change biology, 28(3), 711-726.

Zomer and Tarabucco (2019). Global Aridity Index and Potential Evapotranspiration Climate Database v3. CGIAR-CSI consortium for spatial Information.

10 Annex

10.1 Analytical methods
In preparation

10.1.1 Rock powder analysis:
In preparation

Rock powder sampling protocol

Moisture content at factory gate

X-ray fluorescence analysis:

Bulk mineralogical analysis by X-ray diffraction

Particle size distribution and effective particle diameter

Brunauer–Emmett–Teller Analysis

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

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10.1.2 Soil analysis

In preparation

Soil sampling protocol

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 5: 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 as described in Chapter 3.1.4, 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.

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11.2 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 6: 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.

10.2.2 Rock powder application under U.S. American law
In Preparation

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10.3 Normalized net primary productivity database
In Preparation

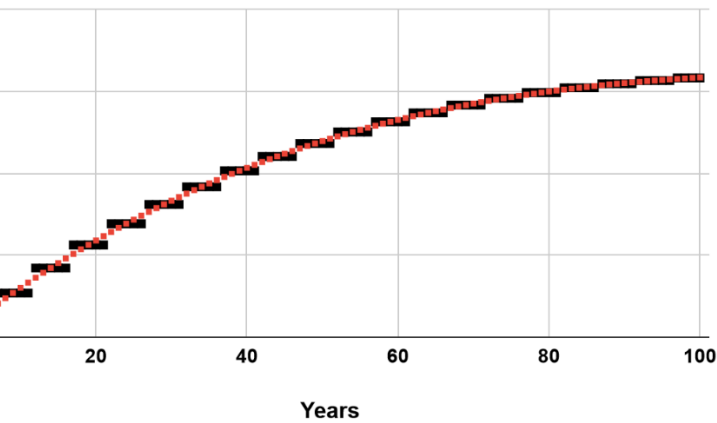*(In preparation)*

10.4 Examples: Expected Rock C-sink curves

South Germany (10 t of Rock Powder)

Accumulation of the Rock-C-Sink Potential

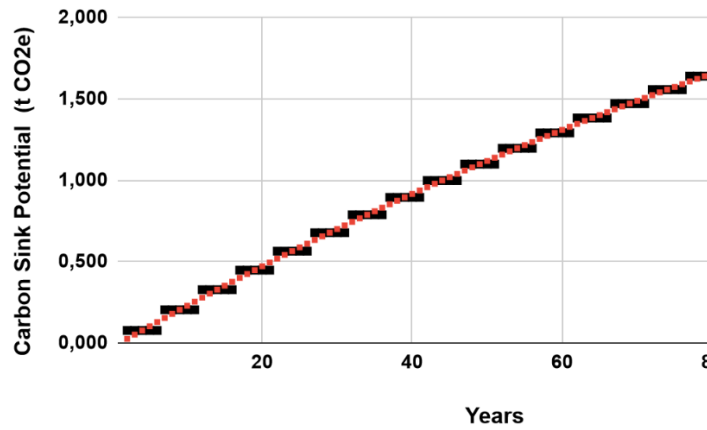■ 5-Year Segments ■ Net C-Sink Potential

Years

: 6.6		Soil temperature: 14.00 °C
	Soil CO₂: 8.000	Soil Moisture (Valid Months): 7

North Spain (10 t of Rock Powder)

Accumulation of the Rock-C-Sink Potenti
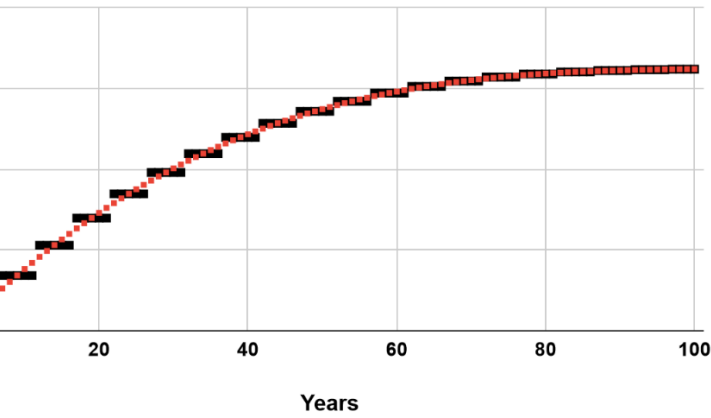
■ 5-Year Segments ■ Net C-Sink Potential

Years

Soil pH 7.2		Soil temperatu
NPPnorm: 0.4	Soil CO2: 4.000	Soil Moist

North Germany (10 t of Rock Powder)

South China (10 t of Rock Powder)

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Approval date:06.04.2023 15:04:33

Accumulation of the Rock-C-Sink Potential

■ 5-Year Segments ■ Net C-Sink Potential

Years

5.6		Soil temperature: 11.5 °C
	Soil CO$_2$: 6.000	Soil Moisture (Valid Months): 9

Accumulation of the Rock-C-Sink Potential

■ 5-Year Segments ■ Net C-Sink Potential

Years
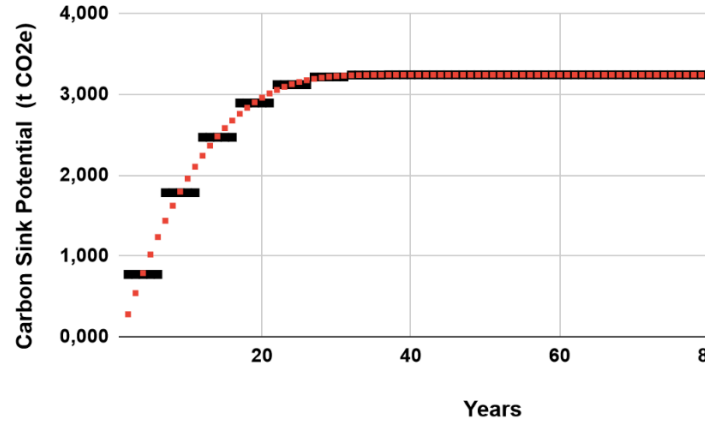
Soil pH: 5.5		Soil temperat...
NPPnorm: 0.6	Soil CO$_2$: 25.000	Soil Moistu...