Certification Protocol for Terresterial Enhanced Rock Weathering

Based on the Rock Stored Carbon metric

[PARTNER LOGOS]

About this document

This document provides a metric and methodology overview for sequestering atmospheric carbon dioxide (CO_2) through Enhanced Rock Weathering (ERW), specifically using olivine. It outlines how to quantify the carbon that operators or groups of operators (henceforth referred to as "Removers") can sequester to receive financial support through Open Natural Carbon Removal Accounting (Oncra) certification for Rock-Stored Carbon (RSC) projects. The metric indicates the amount of CO_2 that will be removed from the atmosphere over time following the application and weathering of a certain amount of rock. The weathering process of olivine takes decades to centuries, and its rate is heavily influenced by the composition of the rock, ambient temperature, groundwater acidity, particle size and biological activity. As olivine weathers, carbon is drawn down into aqueous solutions, eventually adding to the global carbonate-silicate cycle, where it is stored in mineral carbonates and expected to remain out of the atmosphere for 10,000+ years (Lackner, 2003).

This Certification Protocol is aligned with the Technical Assessment Paper and certification methodologies review of the European Union Certification Framework for Carbon Removals, the Oncra Guidelines. Moreover, it is compliant with the ICVCM requirements (see Annex 7 of the Oncra Guidelines).

Version

This document represents version 1.3 (third internal draft) of the Certification Protocol for Terrestrial Enhanced Rock Weathering of January 2025.

Authors

Climate Cleanup is a non-profit foundation and social enterprise funded by members and well-aligned partners. Our mission is to reverse climate change by removing 1500 gigaton CO_2 from the atmosphere with Nature-based Solutions. We do so by fostering systemic conditions for a regenerative economy that doubles nature. We are grateful to our members as without their support this work could not have been done.

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Abbreviations

CB	Certification Body
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CRCF	Carbon Removal Certification Framework
EIA	Environmental Impact Assessment
ERW	CO_2 removal method that accelerates natural rock weathering to capture CO_2 by spreading pulverised silicate minerals, such as olivine, over land where they react with CO_2 and water to form stable carbon compounds.
GHG	Greenhouse Gases
LCA	Life Cycle Assessment
NCRB	Net Carbon Removal Benefit
NDC	National Determined Contributions
RSC	Rock Stored Carbon
SCM	Shrinking Core Model

Glossary

For the purposes of this Certification Protocol, the following definitions apply:

- **Additionality** means the extent to which the certification of a carbon removal activity leads to an additional benefit to the climate beyond a baseline situation without certification;
- **Baseline scenario** means the standard carbon removal performance of comparable activities in similar social, economic, environmental and technological circumstances and [taking] into account the geographical context;
- **Bicarbonate** means hydrogencarbonate, an ion (HCO_3^-) that is formed when CO_2 reacts with water and minerals;
- **Carbonate** means an ionic compound characterised by the presence of the carbonate ion (CO_3^{2-}). The most common is calcium carbonate ($CaCO_3$), the main constituent of limestone;
- **Carbon removal** means the storage of atmospheric carbon through the process of chemical weathering, where CO_2 reacts with silicate minerals to form (bi)carbonate, effectively sequestering carbon;
- **Carbon removal activity** means one or more practices or processes carried out by operators resulting in carbon storage;
- **Carbon removal system** means the sum of all Greenhouse Gas emissions and removals related to the project that are included within the scope of certification;
- **Certificate** means a document published by a certification body or scheme confirming the Net Carbon Removal Benefit of a project operated by a Remover;
- **Certification body** means an independent, accredited or recognised conformity assessment body that has concluded an agreement with a certification scheme to carry out certification audits and issue certificates;
- **Certification scheme** means a scheme managed by a private or public organisation that oversees the certification of Removers or group of Removers;
- **Long-term storage** means the time for which removed carbon is stored before it is released again into the atmosphere.
- **Monitoring** means performing checks at a regular interval to determine whether the quantified and/or delivered Net Carbon Removal Benefit of a project is still valid in reality, with special regard to whether the carbon is still stored;
- **Net Carbon Removal Benefit** means the effect of a carbon removal activity on the concentration of atmospheric greenhouse gases compared to a reference ('business-as-usual') scenario, excluding any avoided emissions or substitution effects;

- **Potential carbon credit** means a record of anticipated carbon dioxide removal associated with a project, issued after verification. These potential credits are not officially recognized as carbon credits at issuance, but allow Removers to already receive financial compensation.
- **Remover** means any legal or physical person who operates or controls a carbon removal activity, or to whom decisive economic power over the technical functioning of the activity has been delegated;
- **Risk of reversal** means the risk that any delivered carbon removals are emitted into the atmosphere before the minimal total lifespan of 100 years;
- **Scope of certification** means the boundaries in space and time within which information related to the project is considered under this Certification Protocol;
- **Validation** means the process of screening and evaluating a project submission and the data delivered by operators of that project;
- **Verification** means the process in which an independent third party with relevant expertise verifies whether the promised Net Carbon Removal Benefit is delivered.
- **Weathering** means the process through which rocks and minerals break down through chemical, physical, or biological interactions. In this protocol, weathering specifically refers to the **chemical weathering of silicate minerals**, a process in which these minerals react with water and atmospheric CO_2, leading to their dissolution and the formation of stable bicarbonates or carbonates.

1. Introduction

1.1 Potential

To be written. This paragraph will clarify how this protocol relates to global effort to quantify enhanced weathering trustworthy and effectively.

1.2 Process

Chemical weathering of rocks is one of the oldest natural processes on Earth and is crucial in regulating the Earth's climate. Exposure to air and water allows rocks to react with atmospheric CO_2, binding it as calcareous products and contributing to long-term carbon storage. This process occurs naturally over geological timescales, but can be accelerated by artificially increasing the weathering rate of silicate minerals. This Enhanced Rock Weathering (ERW) can accelerate weathering by: (1) selecting the most reactive rock material; (2) pulverising the rock into small particles to increase the reactive surface area and thus the mineral dissolution rate; and (3) by distributing the mineral particles in locations with suitable climatic conditions (Meysman & Montserrat, 2017).

Olivine, an abundant and fast-weathering ultramafic silicate mineral, is very suitable for enhanced weathering applications (Montserrat et al., 2017; Schuiling & Krijgsman, 2006; Köhler et al., 2010; Hartmann et al., 2013; Meysman & Montserrat, 2017). This protocol will focus specifically on terrestrial ERW, in which pulverised olivine[1] is spread over a suitable area, as it is a particularly promising technique for atmospheric carbon removal (see paragraph 2.1 for eligible ERW projects).

ERW is increasingly relevant in response to the growing demand for Carbon Dioxide Removal (CDR) technologies (Meysman & Montserrat, 2017). The latest IPCC Assessment Report (2023) recognizes that, in addition to significant emission reductions, CO_2 should be actively captured from the atmosphere. While much attention has focused on carbon capture and storage (CCS), multiple approaches, including olivine weathering, will likely be necessary to meet these targets.

Despite olivine's promising CO_2 sequestration through ERW, current methods fall short in accurately predicting weathering rates and the resulting CO_2 capture across diverse environmental settings (Vink & Knops, 2023). This lack of reliable quantification limits certification needed for reliable carbon credits. This protocol aims to fill this gap by providing a

[1] In this protocol, the term "olivine" will be used to refer to olivine-bearing rock unless specified otherwise.

standardised methodology to quantify CO_2 sequestered specifically through terrestrial ERW with olivine, ultimately enabling reliable certification for carbon credits.

Formula 1 represents the chemical weathering of olivine[2]. As olivine comes in contact with water and CO_2, it dissolves, and the carbon is bound as bicarbonate (HCO_3^-), which is stable near a neutral pH (Hartmann et al., 2013). The bicarbonate can be transported by streams and rivers to seas and oceans, where it eventually precipitates in the form of carbonate minerals (Schuiling & Krijgsman, 2006). The weathering reaction of olivine with CO_2 is irreversible (Vink & Knops, 2023).

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

Formula 1. Olivine dissolution in water (Vink & Knops, 2023)

The weathering of olivine is a gradual process, which typically takes years to decades before achieving substantial carbon capture. The weathering rate and carbon sequestration potential is dependent on the following factors:

- **Particle size**: crushing or milling olivine decreases the particle size and accelerates weathering as it enhances the reactive surface area (Veld et al., 2008). Figure 2 shows how olivine weathering differs for different ranges of particle size.
- **Environmental conditions**: pH, temperature, and water availability affect the chemical weathering of silicate rock (Veld et al., 2008).
    - *pH*: Acidic conditions enhance weathering, as they promote the dissolution of olivine and thus the release of ions that can bind CO_2.
    - *Temperature*: Higher temperatures increase reaction rates, accelerating the weathering process. Mineral dissolution is linked with temperature through the Arrhenius equation, as further explained in Appendix 1.
    - *Water availability*: Water is essential because it facilitates the reaction between olivine and CO_2. It forms a medium for dissolved CO_2 to interact with olivine particles, enabling the formation of bicarbonate ions that eventually lead to carbon sequestration.
- **Biological activity**: Plants, fungi, and soil organisms can contribute to olivine weathering. For example, plant roots excrete organic acids that lower pH, enhancing olivine dissolution and accelerating the binding of CO_2 (Schuiling & De Boer, 2011; Wilson, 2004).

[2] Olivine is a silicate mineral represented by the chemical formula $(Mg,Fe)_2SiO_4$. The proportion of magnesium to iron differs within the solid solution series, ranging from forsterite (the magnesium-rich endmember, Mg_2SiO_4) to fayalite (the iron-rich endmember, Fe_2SiO_4). The endmembers of the olivine series can differ in reactivity and physical properties. In formula (1), iron is excluded because it oxidizes under ambient conditions and therefore does not take up CO_2.

- **Mineral composition**: The composition of olivine varies between mines, particularly in the proportion of **magnesium oxide (MgO)**, which influences the CO_2 binding potential. Higher MgO content indicates a higher quality of olivine, which increases the mineral's capacity to capture carbon (Veld et al., 2008)

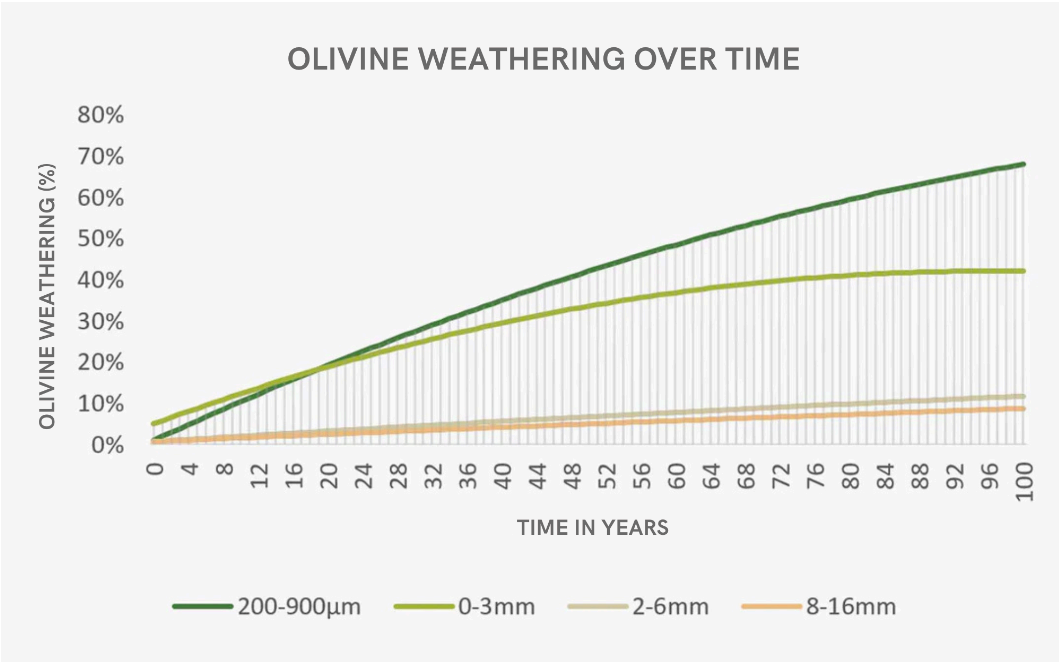

Fig. 2. Olivine weathering over time, based on lab results (translated from greenSand, n.d.). It is important to note that weathering in the field might be faster due to the influence of biological activity.

1.3 Scalability Opportunities and Challenges

Opportunities that make ERW a potentially extremely scalable carbon removal pathway include:

- **Abundance**: Olivine is abundantly present in the Earth's crust, with olivine composing over half of the Earth's upper mantle. Globally, olivine is found on every continent. In Europe, olivine is commercially mined, primarily for the steel industry, with mines located in Norway, Spain, Italy, and Turkey (greenSand, n.d.).

Fig. 3. Map of locations where olivine-bearing rock is currently mined (greenSand, n.d.)

- **Co-benefits**: ERW in soils enhances soil quality by neutralising acidity (similar to traditional agricultural liming). Moreover, it releases beneficial mineral nutrients, reducing the need for fertilisers and potentially improving crop productivity (Ten Berge et al., 2012; Deng et al., 2023)). In marine environments, ERW could reduce ocean acidification (Schuiling & De Boer, 2011; Montserrat et al., 2017).

- **Cost-effectiveness**: ERW is an intermediate cost solution compared to other carbon dioxide removal (CDR) technologies, making it more accessible (Deng et al., 2023; Schuiling & Krijgsman, 2006). Moreover, the costs of the olivine can be partially offset because it replaces conventional materials. Like aforementioned, olivine can replace agricultural lime and buffer pH while providing co-benefits for soil fertility. Hence, it replaces the conventional material (agricultural lime), while reducing the need for additional inputs (fertilizer).

- **No competition for land**: ERW can be applied to agricultural soils without interfering with other land uses, making it suitable within existing crop production systems. This method ensures that the land is not solely used for CO_2 sequestration, but also keeps serving its original purpose. If applied to 50% of global croplands, ERW could potentially sequester up to 2 gigatonnes of CO_2 annually (Deng et al., 2023). Similarly, in civil projects, it can be incorporated into materials like pathways, fulfilling the function of a conventional material (such as sand) while capturing CO_2.

Challenges:

- **Energy-intensive processing**: While the processes of mining, grinding, and transporting rock are well-established, they are energy-intensive and can generate substantial GHG emissions (Hartmann et al., 2013). This affects the feasibility of ERW, as it limits the locations where it would be net-negative and cost-effective. Given these considerations, a grain size of 0-3 mm is recommended because this fraction is widely used in large-scale infrastructure projects for its practicality and cost-effectiveness (Vink et al., 2022). At these particle sizes, the total energy expenditure is typically in the order of 10-20% of the carbon removal impact (Knops, 2020).

- **Environmental considerations**: Weathering of olivine can release trace heavy metals such as nickel and chromium, which can be incorporated in the mineral composition and may pose environmental risks. However, it is worth noting that some of the released metals can also act as essential micronutrients for plants, which can be beneficial as long as their concentrations remain below toxic levels (Haque et al., 2020).

  Depending on crop, rock, dosage, and soil type, there might be elevated concentrations of nickel in plants, potentially entering the food chain (Ten Berge et al., 2012). However, Vink & Knops (2023) indicate that the simultaneous release of magnesium and the increased soil pH during olivine weathering can significantly reduce nickel's toxicity.

  Ten Berge et al. (2012) also note that olivine weathering can increase magnesium (Mg^{2+}) bioavailability and plant uptake. Consequently, calcium (Ca^{2+}) uptake is suppressed, likely due to the competitive uptake of magnesium and calcium by plants. This can cause a nutritional imbalance, as can be seen in natural systems with high Mg/Ca ratios.

  The effects described above, related to the release of heavy metals and magnesium, both increase with the olivine dose. Therefore, in order to avoid nutritional imbalance and nickel accumulation in crop and soil, we advise to avoid high doses (>1630 kg/ha) to minimize risks.

- **Health risks from fine particulate matter**: The grinding of rocks into fine particles, essential for increasing reaction rates, can release airborne particles that could create respiratory health risks. While olivine is used in industry for sand-blasting instead of silica sand as it poses less health risks (Sarkar, 2002), especially particles smaller than

2.5 µm can still pose risks to human health (Vandeginste et al., 2024), so this health risk is particularly relevant for the application of rock powder (Hartmann et al., 2013). To minimise these risks, there should be strict adherence to regulatory standards for air quality and particulate emissions.

- **Uncertainty in weathering rates**: Weathering rates are a source of uncertainty in ERW due to discrepancies between theoretical predictions and real-world outcomes. In situ weathering rates can vary widely within soil environments because of the complexity of biogeochemical reactions (Deng et al., 2023). However, expert knowledge suggests that current estimates are rather conservative, as the accelerating effects of biological activity can substantially enhance the weathering of silicates (Schuiling & De Boer, 2011; Wilson, 2004), implying that ecosystem effects on weathering speed are more likely to be positive than negative.

2. General Activity Requirements

2.1 Eligible Carbon Removal Activities

Projects eligible for certification using this protocol must involve carbon removal activities that meet the following criteria:

- **Terrestrial application**: this protocol version focuses exclusively on terrestrial applications of olivine. Terrestrial ERW involves spreading pulverised olivine over croplands, forests, road-work or other environments where factors like temperature, humidity, and soil conditions facilitate accelerated weathering. Other applications that are not yet certified under this protocol include marine ERW, or Ocean Alkalinity Enhancement (OAE), which involves dispersing ground rock onto the ocean surface, where natural wave action aids the weathering process. Additionally, some experimental ERW projects enhance weathering in contained reactors, where rock particles continuously move through water in a controlled setting.
- **Nature-based Solution (NbS)**: the carbon removal activity should be a Nature-based Solution (NbS), which is defined as an "action to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously benefiting people and nature" (IUCN, 2016). Enhanced Rock Weathering (ERW) aligns with this definition because it accelerates the natural process of rock weathering to remove atmospheric CO_2. In addition to sequestering CO_2, ERW improves soil health, while increasing mineral nutrients like magnesium. Hence, it provides valuable co-benefits for both people and nature.
- The project meets the minimum **Additionality**, **Long-term storage**, and **Sustainability** criteria outlined in paragraphs 3.2, 3.3, and 3.4 respectively.

2.2 Eligible Project Removers

To be eligible for receiving certification on one or more of their projects, Removers must meet the following criteria:

- At least one of the Removers of the project must have legal ownership and/or control over the design, contracting, execution, delivery, and ownership of the ERW project. Legal ownership and/or control over these different project stages may be divided between Removers.
- Right of usage of the land and permission to operate the ERW project. The Remover must have the required permits or licences to operate the ERW project.

- In case of a grouped project in which one Remover, acting as the registration preparer and/or certificate beneficiary, represents (multiple) other Removers, written agreements on liability and certificate ownership must be signed between all Removers.

2.3 Carbon Removal System and Accounting Boundaries

The carbon removal system is defined as the sum of all Greenhouse Gas (GHG) emissions and removals included within the accounting boundaries of the project. Figure 4 shows the carbon removal system boundaries. The following criteria apply to the scope of certification:

- The carbon removal system is limited to modules A1-A5 of a standard Life Cycle Assessment (LCA). Please refer to paragraph 3.1.5 for more information.
  - Any GHG emissions or removals beyond these boundaries (i.e. after module A5) lie outside of the scope of certification and therefore do not impact the quantification of Net Carbon Removal Benefit (NCRB) for RSC projects.
  - The avoided GHG emissions from replacing a reference material with olivine - the emissions that would have been generated to produce and transport that reference material - are also not included in the NCRB. However, if the reference material is clearly defined and its emissions can be reliably quantified, these avoided emissions may be included, provided that justification and evidence are supplied.

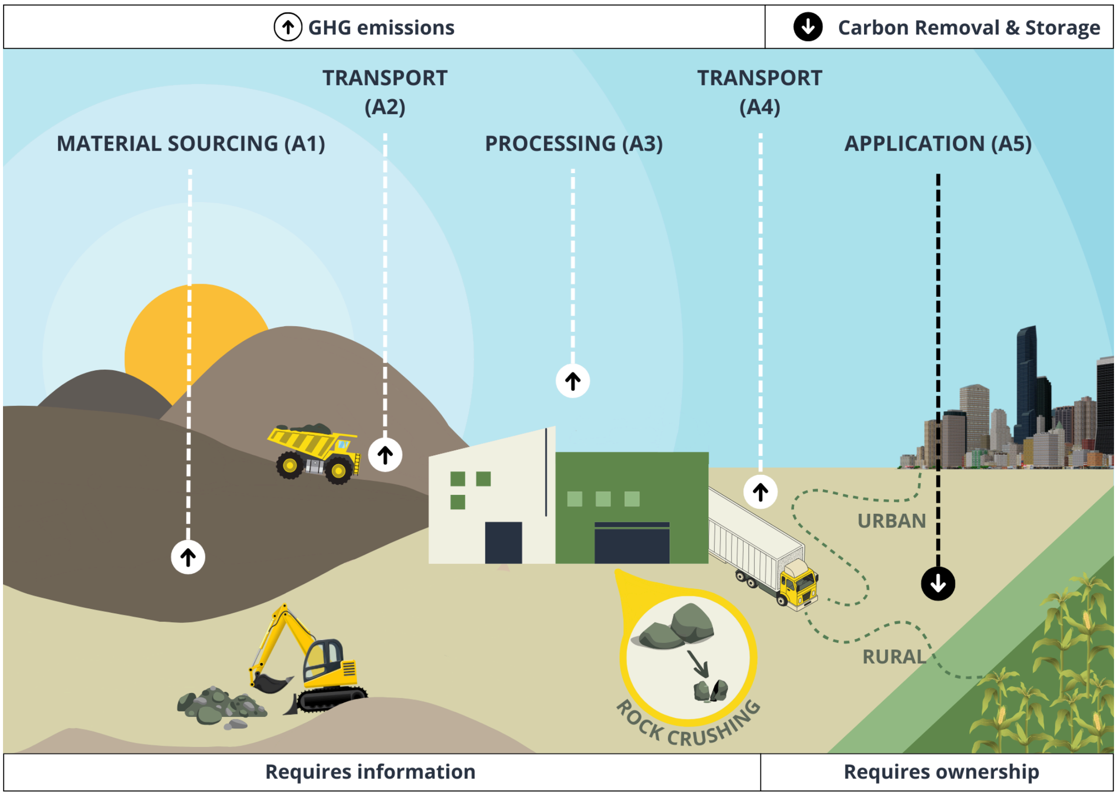

Fig. 4. Carbon removal system, including the removal, storage and emissions of CO_2e in LCA stages A1 to A5.

2.4 Project Timeframe

The assumed project timeframe in this metric is **30 years**. Longer and shorter project durations are permitted, as is extension. Most of the CO_2 binding occurs within the first few decades (see Figure 2), because the weathering rate is highest here, but the total sequestration capacity stretches over a much longer period. Simply put, once a potential credit is sold, the Remover guarantees that the CO_2 will be sequestered permanently in a specified estimated vintage year (the year of physical sequestration), with more sequestration likely continuing well beyond this.

2.5 Issuance of Potential Carbon Credits

Potential carbon credits associated with CO_2 sequestration over the project timeframe can be issued to the Remover, provided they verify both the purchase and application of the olivine. These potential credits, while not officially recognized as carbon credits at issuance, still allow Removers to receive financial compensation. The regulatory requirements for ERW projects depend on the type of project. In the Netherlands, for civil projects, olivine is classified as an approved construction material. Each shipment undergoes thorough inspection during import and meets all legal requirements, ensuring it is safe for use. For these cases, no additional permits are required, and purchase receipts along with photographic evidence are sufficient for verification. However, agricultural ERW projects may require additional assessments and permits to ensure compliance with regulatory standards. For more details on the necessary documentation and certification requirements, please refer to Chapter 4.

2.6 Monitoring

Monitoring must be carried out to ensure the application of the ground rock and the weathering takes place as anticipated. Requirements depend on practical considerations. For instance, continued monitoring may not be necessary if it is both practically impossible to remove the olivine after application and unlikely for weathering to stop if removal occurs. In such cases, applying the principle of proportionality ensures that monitoring requirements are reasonable. For example, in small-scale projects with minimal environmental impact, frequent inspections (e.g., every five years) may not be proportionate to the scope of the problem being addressed. By adhering to proportionality, monitoring requirements can be appropriately scaled to the size of each project. For large scale projects, monitoring must be carried out at least once every ten (10) years.

3. 'QUALITY' Criteria

This section outlines the criteria for certifying carbon removal activities set out by the EU's Carbon Removal Certification Framework (CRCF) Regulation[3]. The acronym 'QU.A.L.ITY' stands for removal activities that are QUantifiable and Additional, provide Long-term storage, and maintain or improve sustainabilITY.

3.1 Quantification

The quantification method in this protocol is specified in the form of the Rock-Stored Carbon (RSC) metric, which describes the quantification process of carbon stored in ERW projects. While Oncra highly prefers direct measurements as the basis for carbon removal accounting, a modeling approach is generally necessary because in situ monitoring often fails to show a sufficiently reliable signal. However, if a measurement method is developed that provides a strong and reliable signal at the scale of the project it concerns, it will be considered for certification under this protocol.

Given these challenges, this protocol allows the use of established quantification methodologies developed by leading organizations, such as Puro.Earth, Isometric, and Csinks. These methodologies are detailed and robust, and Oncra does not aim to duplicate them. Instead, we focus on making those existing protocols more practical and enforceable. Projects that adhere to established methodologies can be certified under Oncra. Hence, Oncra aims to ensure alignment with best practices in the industry while maintaining feasibility for Removers.

Because direct weathering measurements often do not provide a sufficiently strong signal, Oncra relies on modeling as the primary quantification method. What can be directly measured is the amount of olivine applied, which is then used as an input for conservative modeling. Predictive modeling is unavoidable in ERW quantification, and to ensure that carbon sequestration is not overstated, Oncra takes a conservative approach.

Moreover, transparency is key for Oncra. We strive to make all estimation and calculation methods and models developed within Oncra accessible. However, at this time, the Vink & Knops model cannot be published in full, as it was developed externally. Nevertheless, a detailed explanation of its functioning is provided in the next section, as well as in Appendices 1 and 2.

By aligning with best practices and existing quantification frameworks, Oncra aims for this methodology to become an officially recognized approach under the EU Carbon Removal

[3] https://climate.ec.europa.eu/eu-action/carbon-removals-and-carbon-farming_en

Certification Framework (CRCF). Our focus is on ensuring practical implementation, particularly for smaller-scale businesses and innovators, project developers, while maintaining scientific rigor.

3.1.1 Model

The sequestration of CO_2 is quantified using the Vink & Knops (2023) model that calculates atmospheric CO_2 removal by ERW with olivine. Positive emissions from the mining, grinding, and transportation of the olivine are addressed separately through a Life Cycle Assessment (LCA), which ensures that the Net Carbon Removal Benefit (NCRB) is assessed (see paragraph 3.1.5 for LCA details).

The Vink & Knops (2023) model is grounded in empirical research and validated through multiple field experiments. It builds on the TNO report (Veld et al., 2008), which describes the weathering process as a function of temperature and pH, and it has been validated with empirical data from Ten Berge et al. (2012) and Montserrat et al. (2017). Additionally, validation has been supported by experiments from Wageningen University and Research, NIOZ (Royal Netherlands Institute for Sea Research), Movares, and Deltares, ensuring that the model accurately reflects real-world olivine weathering dynamics.

The Vink & Knops model is based on the Shrinking Core Model (SCM), which is a widely recognized approach that simulates the dissolution of mineral particles over time. The SCM describes how solid particles are gradually consumed via dissolution or chemical reactions, causing them to shrink in size over time. In this model, particles are assumed to be spherical, and their diameters decrease proportionally as weathering progresses.

One of the strengths of the Vink & Knops model is that it incorporates a particle size distribution, unlike most weathering studies that assume monodisperse particle sizes (where all particles are uniform in size). Real-world olivine batches consist of particles with a wide range of sizes, from micrometres to millimetres, and neglecting this distribution can lead to large variations in the estimation of weathering rates and CO_2 uptake, as noted by Hangx and Spiers (2009). By considering the full range of particle sizes, the Vink & Knops model improves the accuracy of carbon sequestration estimates.

Ultimately, the model calculates the decrease in particle diameter over time, modelling the weathered mass and corresponding CO_2 sequestered at each time stamp.

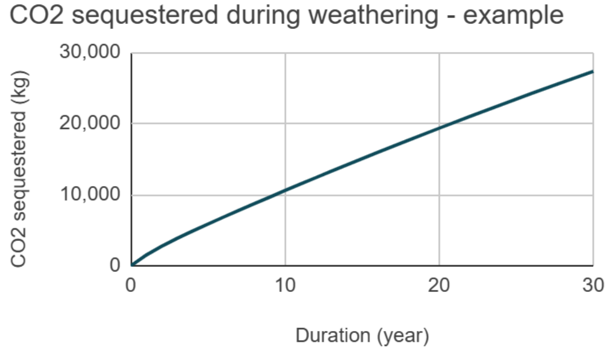

Fig. 5. Example of model output - Cumulative CO_2-sequestration over time.

To ensure the model does not overstate carbon sequestration, a conservative weathering rate of approximately 0.8 - 1 kg CO_2 sequestered per kg of olivine is applied, depending on the MgO content, an indicator of mineral quality. This rate is intentionally set below the theoretical maximum of 1.25 kg CO_2 per kg of olivine (Hartmann et al., 2013) to remain conservative. The sequestration rate calculation is explained in Appendix 2. This approach aligns with the principles of conservatism outlined in the Technical Assessment Paper of the ICF (2024).

Key inputs to the model include the composition of the olivine-bearing rock, specifically the MgO-content, and the particle size distribution, both determined by the olivine supplier. Additionally, the dosage of olivine applied in tons per hectare is required by the model, particularly when determining if the olivine is mixed with other materials, such as sand. The dosage is project-specific and determined by the Remover.

Moreover, the model incorporates environmental conditions as inputs. Temperature is included, with projections for future increases based on data from [t.b.d]. Additionally, soil pH is factored in, as it, together with particle size, has the most influence on the weathering rate (Veld et al., 2008). In urban environments where soil interaction is limited, the pH of rainwater - typically slightly acidic - can serve as an indicator. However, in scenarios where olivine is integrated into the soil, such as in an agricultural context, on-site pH measurements may be needed. These measurements will be conducted according to Oncra's soil sampling protocol. When farmers have previously conducted soil analyses, their existing pH data can be used.

For a detailed breakdown of the formulas used in this model, please refer to Appendix 1.

3.1.2 Model Applicability Limitations

The model assumes sufficient moisture availability to sustain olivine weathering, as the reaction continues as long as there is enough water and air. Prolonged periods of drought could potentially reduce weathering rates due to moisture limitations, which could reduce model accuracy. However, Vink et al. (2022) observed in their field trials that the moisture availability under natural precipitation conditions in the Netherlands does not significantly limit olivine weathering. Nevertheless, the assumption that moisture availability is sufficient might not hold internationally, particularly in more arid regions. Additionally, since the model is validated using data from studies conducted in the Netherlands, its applicability to other regions with differing climatic conditions may be constrained. In general the model is expected to hold up as conservative for more moist and warm regions. Limitations will be considered during the verification process, and potential adjustments will be made to ensure the model remains conservative in diverse conditions.

3.1.3 Net Carbon Removal Benefit

$$NCRB = CR_{total} - GHG - CR_{baseline} \quad (2)$$

symbol	description	unit
NCRB	Net carbon removal benefit	t CO_2e
CR_{total}	Total project carbon removal - as determined by model	t CO_2
GHG	Direct and indirect increase in GHG emissions	t CO_2e
$CR_{baseline}$	Carbon removals under the baseline scenario	t CO_2

For the NCRB, the following criteria apply:

- All quantities in Formula (2) shall be denoted with a positive (+) sign and shall be expressed in tonnes of carbon dioxide equivalent.
- Removers shall deliver the measurements needed to quantify the net carbon removal benefit for their project (see also paragraph 4.1) and clearly distinguish the different elements of Formula (2).
- Removers shall highlight any cases of uncertainty regarding the quantification of any of the elements of Formula (2) and shall make a justifiably conservative choice or estimate. For example, when a range of values is available for the quantification of an element or sub-element of Formula (2), Removers shall choose a value on the lower end of that range.

3.1.4 Total Carbon Removals

Total project carbon removals for an ERW project are defined using the model explained in paragraph 3.1.1, expressed in tonnes of CO_2.

3.1.5 GHG Emissions

GHG emissions caused by the project, in the process of sourcing, processing, and transporting the olivine, must be subtracted from the project's Net Carbon Removal Benefit, as shown in Formula (2). This is done through a Life Cycle Assessment (LCA), which quantifies emissions across the entire product or process lifecycle, from raw material extraction to transport and eventual use.

The relevant LCA (stage A1-A5) should be conducted by the Remover or another involved party and be included in the calculations of CO_2 permanently sequestered, as aforementioned in paragraph 2.3. Emissions are primarily generated during the mining, crushing, milling, and transport of the rock. These can be accounted for with a general LCA (stages A1-A3) that takes the arrival of the shipment as the final point in the process. However, it is also important to produce a rough estimate for the average emissions per project. Most of these emissions result from transporting the rock to project locations (stage A4).

It is best to ensure that an ERW project has additional benefits. In other words, olivine should replace an already used material and its function, rather than be added to an environment with the sole objective of CDR. This approach can help establish a more solid business case for the Remover. Olivine can replace existing material for civic purposes (around railways, on sand paths etc.), coast enhancement, and agricultural uses (for example, as a liming material). Existing projects are listed in [paragraph containing pilot projects, t.b.d.] The avoided GHG emissions of producing and transporting the reference material will not be included in the calculation of the NCRB to maintain a clear and conservative assessment of net carbon sequestration.

3.1.6 Baseline Scenario

The baseline scenario is defined as "the standard carbon removal performance of comparable activities in similar social, economic, environmental and technological circumstances and [taking] into account the geographical context"[4]. In this protocol, the baseline carbon removal ($CR_{baseline}$) is set to zero because ERW introduces a process that would not naturally occur at the project location. Including a baseline would inaccurately suggest that some level of carbon removal would happen without intervention, which is not true for ERW projects. Therefore, no baseline is included to ensure that all quantified carbon removal reflects only the additional benefit provided by the project.

3.2 Additionality

To be eligible for certification, the project shall comply with the following additionality criteria:

a. Any carbon removal and/or storage mandated by law or directly subsidised, either in total tonnes of CO2e or as a percentage of total project carbon removals (CR_total), should be excluded from the project's Net Carbon Removal Benefit (NCRB). A subsidy is considered directly relevant if it directly supports CO_2 removal. Subsidies or legal requirements that do not directly impact carbon removal efforts are considered irrelevant to this certification protocol. Moreover, the removal pathway or project should not cover climate mitigation measures that are included in the National Determined Contributions (NDC) of the country where the removal is effectuated.
b. The carbon removal associated with the project shall not be double counted. This means that no two certificates are issued for the same tonne of CO2e removed. Removers shall be held liable for any occurrence of double counting. Three types of double counting shall be checked:

[4] European Commission, Directorate-General for Climate Action, (2022). "Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL establishing a Union certification framework for carbon removals". COM/2022/672. Article 4(5): p.11.

i. Removers shall not certify the net carbon removal benefit of their projects certified by Oncra under any other carbon removal certification scheme.

ii. Removers shall ensure that the rock carbon removal accounted for are not claimed anywhere in their supply chains. If the carbon removals have already been claimed, these removals shall be excluded from the quantification of the RSC.

iii. Once the certificate rights are sold to a third party, Removers shall refrain from claiming the quantified net carbon removal benefit, using it as a substantiation of climate neutrality claims, or including it in their carbon accounting, unless the relevant purchase agreement(s) explicitly state(s) that the buyer refrains from these claims.

c. The revenue from carbon certificates should lead to carbon sequestration. The Remover must declare that they reinvest the revenue from the transition financing[5] for carbon removal.

d. A duty of accountability must be provided by the Remover, which shows that the transition finance provided for the carbon removal is a significant component of the business case of the project.

3.3 Long-Term Storage

Long-term storage describes the time for which removed carbon is stored before it is released again into the atmosphere. In ERW applied to soils, carbon sequestration is considered highly stable, with an expected storage of approximately 10,000 years (Lackner, 2003) and minimal risk of reversal from natural processes or human activity (Allen et al., 2020).

To support long-term storage and mitigate any risks of carbon reversal, a 20% buffer pool (Holding Pool) will be applied. Given that ERW is a carbon removal pathway with little risk of reversal (Allen et al., 2020), this Holding Pool will primarily serve as insurance for project-related uncertainties. From the 20% Holding Pool, 15% is allocated for project-specific risks, such as project delays or cancellations, and 5% is general holding, for example in the event of company bankruptcy. Once the olivine application is verified, the 15% project holding is freed, as removing rockdust from agricultural land or roadwork is practically impossible. For more information on holding pools and long-term storage, please refer to the Oncra Guidelines.

3.4 Sustainability

To comply with the minimum sustainability requirements of this Certification Protocol, Removers shall comply with the following criteria for environmental and social impact:

[5] 'Transition financing' refers to the income from carbon credits

a. The project shall have at least a neutral (“No Net Harm” principle) impact on the following six sustainability objectives:
    i. Climate change mitigation beyond the NCRB as quantified according to Formula (2) in paragraph 3.1.3;
    ii. Climate change adaptation;
    iii. Sustainable use and protection of water and marine resources;
    iv. Transition to a circular economy;
    v. Pollution prevention and control;
    vi. Protection and restoration of biodiversity and ecosystems.
b. To provide evidence of the compliance with the sustainability objectives of criterion (a), Removers need to deliver an Environmental Impact Assessment (EIA). This EIA must be updated every five years, provided it is proportional to the scale of the project. For instance, small projects may be exempt from updates unless objections are raised by relevant authorities. If well-enforced environmental regulations are already in place, an EIA may not be necessary.

   Furthermore, to prevent pollution, the olivine-bearing rock used in ERW projects must undergo strict checks for hazardous materials. For instance, in the Netherlands, olivine is classified as an approved construction material. It has been tested and meets all legal requirements, ensuring it is safe to use in civil ERW projects.
c. Removers may report on any additional benefits generated by the project beyond the minimum sustainability requirements. These co-benefits need to be communicated transparently, concisely and clearly by the Remover to Oncra.

4. Measurement, Reporting and Verification Requirements

4.1 Measurement

When submitting a project for certification following the RSC Certification Protocol, Removers shall ensure that the following data is measured:

- Mineral composition of the olivine, specifically MgO-content.
- Particle size distribution.
- The surface area of the application site (over which the rock is applied)
- The total mass of applied olivine
- Soil pH measurements. For urban projects, the pH of rainwater is used as an indicator. In agricultural settings, on-site soil pH measurements are typically required, following Oncra's soil sampling protocol. If farmers have existing soil analyses, their previously recorded pH data may be used.

When certain measurements are not available, data from scientific literature can be used when deemed reasonable and within proportionality by Oncra and the Certification Body. This data must be: location relevant (from the same or similar species, geological location and environmental condition) and time relevant (from within the last 10 years).

4.2 Reporting

When submitting a project for certification, Removers shall submit measurements outlined in paragraph 4.1 by writing a project plan or filling in a project submission form as provided by the certification scheme. Any proofs shall be separately submitted as appendices.

Removers shall ensure the following information is reported and provided to Oncra:

- Description of the project:
    - Name of project
    - Geo-location of the application site.
    - Surface area (e.g. map of the application site), including current land-use.
    - Photo of the application site and the application itself.
    - Application method, including application depth.
    - Origin of the rock material, including any relevant supply chain information.
    - Final legal ownership: name and ID of the project operator (final carbon value owner).
    - Photo of the project operator.
    - Written description of major project risks.

- Right of usage: a proof of the right of usage of the land that the ERW project is present on and/or required permits or licences to operate the ERW project (e.g. environmental permit, soil amendment permit, business licence).
- Environmental Impact Assessment: proof of adherence with the minimum sustainability requirements through an EIA (see paragraph 3.4).
- Life Cycle Assessment (LCA), as described in paragraph 2.3 and 3.1.5.
- Signed contract of liability for double-counting.
- Eligibility of Removers: description of organisations involved including legal information, roles in the project and people involved. In case of grouped projects, a written and signed agreement on liability and beneficiaries is required.

4.3 Verification

Projects must seek verification from an independent Certification Body (CB) in compliance with the following criteria:

a. Verification by the CB must include the calculations on the amount of (expected) carbon storage, the baseline carbon, the amount of emissions (LCA calculations) and risks of the project.
b. After verification, Removers must provide Oncra with a verification report signed by the CB, that clearly states which documents and data the CB has verified
c. If a CB rejects the project verification request, written justification must be provided. After rejection by a CB, Removers must re-submit their project to Oncra for validation. Removers may re-submit their project up to two times
d. Once a verification report is delivered and accepted by Oncra, Removers shall receive Oncra certification.

5. Next Steps

This is the second internal draft of the *Oncra Certification Protocol for Terrestrial Enhanced Rock Weathering*. Several steps have been taken and will have to take place before the protocol is finalized:

1. First feedback round: the Climate Cleanup team provided internal feedback.
2. Second feedback round: feedback provided by selected ERW experts in the Climate Cleanup network. This is done to ensure a higher quality of the protocol and to implement the expertise of those experts.
3. Third feedback round: through publication on the Climate Cleanup website, an open feedback round by a larger audience is initiated.
4. Publishing the protocol: the finished version of the Certification Protocol will be published.
5. Trial certification: a trial certification will be performed with feedback from ERW experts.
6. Certification of ERW projects: different projects will be certified according to the protocol.

We plan on including some pilot projects to illustrate the methodology outlined in this protocol.

For future versions of this protocol, we could look into the use of alternative silicate minerals, like wollastonite or basalt, and explore other application methods, including marine application.

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Appendix 1

The model by Vink & Knops (2023) aims to quantify olivine weathering, with a focus on CO_2 sequestration and the ecotoxicological risks of nickel. The model incorporates a particle size distribution and models the kinetic size-dependent dissolution of olivine for different environmental conditions.

The key aspects underlying the model include:

- **Size-fractionated weathering of olivine**
  As aforementioned, the model is based on the Shrinking Core Model (SCM), which includes variations in olivine particle sizes to better represent actual weathering rates. Weathered mass is calculated separately for each size fraction, and then added up for all time stamps, allowing for more precise predictions compared to assuming a single, uniform particle size. Smaller particles weather more quickly due to their larger surface-to-volume ratio.

- **PH-dependent mineral dissolution rate**
  Olsen (2007) reported a strong relationship between pH and the mineral dissolution rate (r), noting a distinct break around pH = 6:
  - pH<6: $\log(r) = -0.48 \times pH - 6.9$
  - pH≥6: $\log(r) = -0.18 \times pH - 8.8$

- **Temperature-dependent rate constant**
  The rate constant (k_T) depends on temperature and is defined by the first-order Arrhenius equation:

  $\ln k_T = \ln k_{T.Ref} - E_a / R \, (1/T - 1/T_{ref})$
  - T = temperature (K)
  - E_a = activation energy (J/mol)
  - R = gas constant (J/mol·K)

  The Arrhenius principle was applied to each of the size fractions. For their study, Vink and Knops used the dissolution rate derived by Vink et al. (2022) who used two olivine types in field experiments in soil under ambient conditions. Model parameters are:
  - $\ln k_T = 7.43 \cdot 10^{-11}$ mol·m^2·s^{-1}
  - E_a = 8.31 J/K·mol
  - T = 295K
  - T_r = 284K

For this study, we simplified and adapted the model with Pol Knops to suit our primary purpose of quantifying the weathering and specifically the CO2 sequestration. This adaptation of the original model excludes the ecotoxicological assessment present in Vink & Knops' initial model, which used a Biotic Ligand Model (BLM) to evaluate nickel toxicity. Their findings indicated that, at typical application rates, the release of magnesium and the resulting pH increase from olivine weathering significantly lowered nickel toxicity, supporting the ecological suitability of olivine applications.

The table below is an output of the model, based on an example particle size distribution:

Graphs							Rate (per year)
Duration	Erosion rate	Olivine dissolved (|cumulative)		CO2 sequestered		Weathering	Olivine Dissolved (/yr)
(year)	(um)	(kg)	(%)	(kg)	(ton)	(um/yr)	(kg/yr)
0	0.00	0	0.0%	0	0		
1	0.76	1,519	1.5%	1,519	2	0.76	1,519
2	1.51	2,756	2.8%	2,756	3	0.76	1,237
3	2.27	3,855	3.9%	3,855	4	0.76	1,098
4	3.03	4,882	4.9%	4,882	5	0.76	1,027
5	3.79	5,871	5.9%	5,871	6	0.76	989
6	4.54	6,837	6.8%	6,837	7	0.76	966
7	5.30	7,789	7.8%	7,789	8	0.76	951
8	6.06	8,728	8.7%	8,728	9	0.76	940
9	6.81	9,658	9.7%	9,658	10	0.76	930
10	7.57	10,579	10.6%	10,579	11	0.76	921
11	8.33	11,491	11.5%	11,491	11	0.76	912
12	9.09	12,395	12.4%	12,395	12	0.76	904
13	9.84	13,290	13.3%	13,290	13	0.76	896
14	10.60	14,178	14.2%	14,178	14	0.76	887
16	12.12	15,928	15.9%	15,928	16	0.76	875
18	13.63	17,646	17.6%	17,646	18	0.76	859
20	15.14	19,333	19.3%	19,333	19	0.76	844
22	16.66	20,989	21.0%	20,989	21	0.76	828
24	18.17	22,615	22.6%	22,615	23	0.76	813
26	19.69	24,211	24.2%	24,211	24	0.76	798
28	21.20	25,777	25.8%	25,777	26	0.76	783
30	22.72	27,314	27.3%	27,314	27	0.76	768
35	26.50	31,024	31.0%	31,024	31	0.76	742
40	30.29	34,561	34.6%	34,561	35	0.76	707
50	37.86	41,119	41.1%	41,119	41	0.76	656
100	75.72	65,806	65.8%	65,806	66	0.76	494
150	113.58	81,311	81.3%	81,311	81	0.76	310
200	151.44	90,551	90.6%	90,551	91	0.76	185
250	189.30	95,661	95.7%	95,661	96	0.76	102
500	378.59	99,983	100.0%	99,983	100	0.76	17

Appendix 2

Formula 1 represents the chemical weathering reaction of olivine. The carbon sequestration rate of olivine is determined using stoichiometric relationships and depends on the fraction of MgO present.

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

Formula 1. Olivine dissolution in water (Vink & Knops, 2023)

As can be seen from Formula 1, the stoichiometric ratio of Mg:CO_2 is 1:2. Hence, for each mole of MgO, two moles of CO_2 are sequestered. To determine the sequestration potential, the most efficient method is to measure the MgO content using XRF (X-ray fluorescence), a quick and inexpensive technique. The calculation method can be found in the accompanying Excel file. To illustrate, a material containing 37% MgO corresponds to approximately 0.81 kg CO_2 sequestered per kg of material.