



Actions required to secure the large-scale deployment of the leading CDR approaches to meet EU climate targets

C-SINK– FACTSHEET LECTURE 3 DELIVERED BY ICAMCYL,
KUL, MEM, PAS & BOL.

CARBON DIOXIDE REMOVAL TECHNOLOGIES (CDR-T): Enhanced Rock Weathering (ERW)

INTRODUCTION

Carbon dioxide (CO₂) is regarded as the primary greenhouse gas (GHG) responsible for climate change, with atmospheric concentrations having risen by 50% compared to pre-industrial levels due to human activities, notably fossil fuel burning and deforestation (Smith et al., 2024). While efforts are underway to reduce GHG emissions by transitioning to renewable energy sources, these actions alone are insufficient to meet the Paris Agreement goals (UNFCCC, 2015). Hence, the development of carbon dioxide removal (CDR) methods, also known as negative emission technologies (NET), is imperative. These technologies enable the removal of current and previously accumulated CO₂ emissions and help compensate for emissions from sectors that are difficult to decarbonize, thus facilitating the achievement of net-zero emissions. CDR technologies encompass various conventional and novel methods, including afforestation, bioenergy with carbon capture and storage (BECCS), biochar soil amendment, direct air capture (DAC), enhanced rock weathering (ERW), and ocean alkalinity enhancement (Smith et al., 2024).

C-SINK is a four-year European-funded project that aims to build a standardized and transparent European CDR market with trustworthy accounting methodologies based on robust MRV pre-standards and policy strategies. Comprehensive scientific assessments will be made of the various CDR approaches in terms of their potential uptake of CO₂, their safety, and other impacts.

GLOSSARY

Basalt rocks: They are extrusive igneous rocks (volcanic) that are low in silica content, dark-coloured, and rich in Fe and Mg. Basalt usually exhibits a porphyritic structure with phenocrysts of olivine, pyroxene (augite), and feldspar in the matrix¹.

Carbonates: Include all forms of inorganic carbon, such as calcium and magnesium carbonates.

Carbon Dioxide Removal (CDR): Refers to activities that remove CO₂ from the atmosphere and store it permanently (IPCC, 2018).

Mafic and ultramafic rocks: Mafic and ultramafic rocks are rock types consisting predominantly of mafic (Mg- and Fe-rich) minerals (e.g., olivine, pyroxene, and amphibole) with a low content of silica. The ultramafic rocks are defined within an olivine, orthopyroxene, and clinopyroxene ternary diagram².

ERW PROCESS

Rocks and mining by-products or wastes are commonly composed of several minerals, or less frequently of one mineral type. When these are exposed to wind, rain, or waves at various temperatures, they are eroded, releasing dissolved ions into water in a natural process called weathering. During this process, atmospheric CO₂ reacts with water, forming a weak acid (carbonic acid or H₂CO₃), which causes mineral dissolution (Figure 1). If rocks contain high concentrations of Ca-, Mg-, and Fe-rich minerals (e.g., olivine, pyroxene, amphibole group minerals), they dissolve, releasing cations and anions in water. Several chemical reactions for mineral dissolution

¹ <https://www.britannica.com/science/basalt>

² <https://geologyistheway.com/igneous/classification-of-ultramafic-rocks/>



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and carbon sequestration are involved in the ERW process (Vandeginste et al., 2024). The carbonic acid dissociation in relation to pH is described in Figure 1.

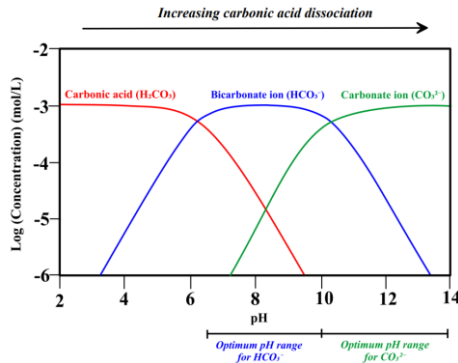
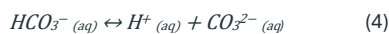
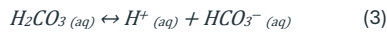
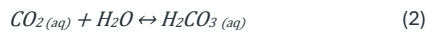


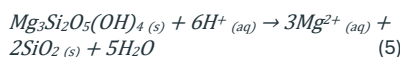
Figure 1. Influence of pH on carbonic acid dissociation in an idealised solution (modified after Rackley, 2017).

Mineral dissolution

Atmospheric CO₂ gas dissolves in water and forms carbonic acid (Equation 1-4). Bicarbonate and carbonate ions become available in the solution, the extent of which depends also on the pH of the water (Figure 1).



Then, the formation of carbonic acid aids in the dissolution of (ultra)mafic rocks and minerals and leads to the release of cations (Equation 5). The dissolution of these rocks and minerals will cause an increase in the pH of the water, and thus, a larger availability of bicarbonate and, in particular, carbonate ions. In this way, carbon is removed from the atmosphere and trapped as bicarbonate and carbonate ions in water.

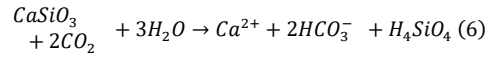


Carbonate sequestration:

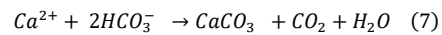
CDR by ERW of crushed ultramafic rocks (e.g. olivine) applied to soils can be calculated via two pathways (Beerling et al. 2020):

Pathway 1) the transfer of weathered base cations (Ca²⁺, Mg²⁺, Na⁺,

and K⁺) from soil drainage waters to surface waters that are charge balanced by the formation of HCO₃⁻ ions and transported to the ocean Equation (6).



Pathway 2: The formation of pedogenic carbonates is described by Equation (7) for calcium carbonate formation.



ERW DEPLOYMENT PROCESS

The ERW stepwise deployment process, including critical control points (CCP) and key performance indicators (KPI), are illustrated in Figure 2.

1) Source Materials: The physicochemical properties of the source material are the first factor that controls the carbon dioxide sequestration potential of ERW. These include chemical composition, mineralogy, and particle size.

2) Comminution: Material that is acquired finely grained may skip the process of comminution and be readily available for transport. Should comminution be required, this generates an extra cost- and energy-intensive step.

3) Transport: The materials are transported to targeted locations for dispersion. These locations can be either arable lands or seashores, providing different concomitant benefits. In C-SINK, the CDR potential of mining wastes in situ is also tested since the

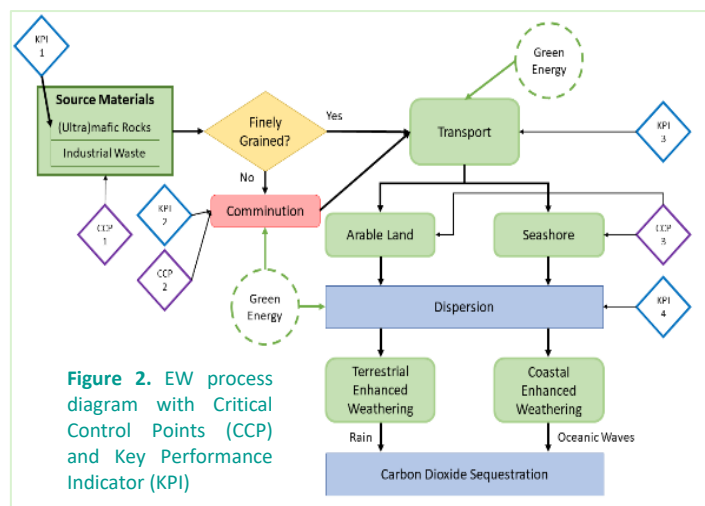


Figure 2. ERW process diagram with Critical Control Points (CCP) and Key Performance Indicator (KPI)



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use of these wastes avoids extra costs and transport emissions.

4) Dispersion: Dispersion on arable land could increase crop growth due to nutrient addition, while dispersion on the seashore could reap the benefits of wave action for faster dissolution.

5) Carbon dioxide sequestration: once dissolved, source materials increase the alkalinity of the solution, thereby creating a potential for CO₂ to be sequestered as bicarbonate or carbonate minerals. Using green energy for comminution, transportation, and dispersion processes is necessary to increase CDR and meet climate targets.

ERW PARAMETERS INFLUENCING THE CDR POTENTIAL

Different researchers such as Strefler et al., (2018) Beerling et al., (2020) Smet et al., (2021), and Bullock et al., (2023) agree that the CDR potential through ERW depends on several parameters such as the type of rocks, grain size and surface, temperature, soil type, and climate factor, pH, and particular plant species.

❖ Type of rocks derived from mine wastes and other by-products.

Olivine is the most abundant and fastest-weathering magnesium silicate mineral on Earth (Smet et al., 2021, Bullock et al., 2023). This means that olivine-rich rocks have the highest potential for both carbon dioxide removal and soil fertility improvement.

Ultramafic igneous rocks (e.g. peridotite, dunite, harzburgite, kimberlite) consist mostly of olivine, and their metamorphic equivalents (e.g. serpentinite rock) are composed of serpentine, along with other Fe-Mg silicate minerals. These rocks have the highest CDR potential (up to 0.8 ton CO₂ per ton of applied ultramafic rock dust), but they contain low concentrations of nutrients and high heavy metals content (e.g. Ni and Cr), which can be an environmental risk (Strefler et al., 2018).

Mafic rocks (e.g. basalt, gabbro, diabase) have a lower CDR potential (about 0.3 ton

CO₂ per ton of applied basalt) as they contain less olivine and Fe-Mg silicate minerals (Strefler et al., 2018). However, they contain a range of other minerals that release Ca, Na, K, and P upon dissolution, making them excellent natural fertilizers – and their Ni and Cr contents are not as high as for ultramafic rocks.

❖ Grain size and surface

The reactive surface area of the CDR material is increased by reducing the grain size, therefore increasing the rate of weathering (Beerling et al., 2020, Smet et al., 2021). However, the energy and cost involved with crushing and grinding (ultra)mafic rocks put limitations on the achievable grain size. Therefore, using mining wastes is highly recommended since it decreases the energy requirements of ERW as extra comminution is not necessary.

❖ Soil type and climate

Renforth (2012) and Smet et al. (2021) showed that high temperatures accelerate the weathering process (e.g. tropical climate) and intense rainfall is crucial since water is necessary for the chemical reaction to take place because it provides a sufficient supply of CO₂.

❖ Plant species

Afforestation can considerably increase the weathering rate of applied silicate rock powders (Smet et al., 2021). Chemical, physical, and biological soil properties are very different near plant roots. Microorganisms also boost the physical and chemical breakdown of silicate grains in the soil (Calabrese, 2022).

ERW TIMEFRAME FOR CDR

The removal of CO₂ through ERW, thus through a mineral carbonation process, is not immediate (Chiquier et al., 2022). Carbonation rates range from a few months to a few decades (Renforth, 2012; Strefler et al., 2018 and Beerling et al., 2020). Bullock et al. (2023) suggested 100 years, while Smet et al. (2021) referred to rock weathering not only removing CO₂ from the atmosphere but also initiating permanent carbon sequestration. However, Hangx &



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Spiers (2009) estimated a timeframe of 23 years for the full dissolution of 10 μm olivine particles on beaches. This duration increases to 233 years for a grain size of 100 μm .

C-SINK field trial data point out that a multitude of factors such as grain size, climatic conditions, rate of mineral application, etc., affect the timescales in which CO_2 removal can be achieved by ERW.

REVERSAL RISK

C-SINK ERW upscaling work considers that mineral precipitates are a relatively stable form of CO_2 removal. In the case of calcium carbonate formation, it is susceptible to re-dissolution (and thus CO_2 release) if it encounters acidic fluids. Therefore, the risk of reversal can be high in such a scenario. However, the environment where the mineral precipitates (e.g., deep in the ground) can reduce this risk. Strefler et al. (2018) suggested that compared to other CDR technologies, ERW has low technical risks.

COSTS, TRL

According to Schuiling & Krijgsman, (2006), the cost of the technology is estimated to be on the order of 14 €/t of CO_2 . It is supposed to be a competitive price compared to the other technology solutions. However, an economic cost assessment by Strefler et al. (2018) indicated that ERW costs were below 67 € t rock⁻¹ for grain sizes around 20 μm , leading to costs of carbon removal around 57 € per t CO_2 for dunite and around 191 € per t CO_2 for basalt. This is higher than most recent cost estimates for afforestation (23 € t CO_2) and BECCS (34 € t CO_2), but still lower than expected costs for direct air capture (412–546 € t CO_2). If co-benefits from nutrient supply or soil improvement are taken into account, the competitiveness of ERW will further increase. Subsequently, Geden & Schenuit (2020) mentioned that the method's potential is estimated to be 2–4 Gt CO_2 , at 48–192 € per tonne of CO_2 removed.

Finally, C-SINK experts agree with Beerling et al., (2020) related to the cost assessment

estimating that ERW could cost between 72-239 €/tonne theoretically. However, within the C-SINK project, a few field trials will be developed to have assessments of the MRV cost and removals. Regarding TRL, Smith et al., (2023) ranked 3-4 for ERW, which is considered a medium level. Therefore, a TRL7 will be conducted in the C-SINK project.

TYPICAL SCALE

No typical scale of CO_2 has been found in the literature because of incongruences and disagreements between researchers. These incongruences were summarised by Samaniego et al. (2023), and since the IPCC suggested a range for the potential to remove carbon of 0.72 to 95 Gt CO_2 yr⁻¹, recent enhanced weathering experiments have suggested the technique may be up to three times less efficient than previously suggested by Amann et al. (2020).

On the other hand, Hangx & Spiers (2009) estimated that the weathering of 1 tonne of mafic (e.g. basalt) and ultramafic rocks (e.g. dunite) can remove ~ 0.3 and 0.8 tonnes of CO_2 , respectively, indicating a considerable overall theoretical potential.

Overall, enhanced weathering is still a relatively new CDR technology to the industry and one of the major unknowns in this technology is the actual amount and timescale of CO_2 sequestered.

SCALABILITY AND LIMITING FACTORS

As for technical and operational factors, Samaniego et al. (2023) summarised the scalability of ERW in terms of limiting factors. Although the ERW technology has been put into practice in several case studies, it is classified as a slow solution due to the geochemical reactions of the process to transform some minerals into carbonates. Besides, the potential CO_2 removal is a crucial uncertainty that should be solved for further scaling. However, there may be a preference for the use of mining by-products or wastes for enhanced weathering rather than the exploitation of new mines to access materials.

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Regarding policies and regulations, if ERW would be deployed at a significant scale, new international mechanisms for monitoring, verification, and reporting, including mechanisms that account for the transboundary effects of the approach would be required (Samaniego et al., 2023). Also, new policies for transporting and handling ‘waste’ or new classification of mine waste to be a ‘by-product’.

Besides, researchers such as Beerling et al. (2020) extrapolated laboratory weathering rates to the field scale to calculate CDR rates by enhanced rock weathering, ERW technology applying Monte Carlo analysis, a well-recognised method. Recently, ERW as CDR-T has been upscaled and modelled by Beerling et al. (2024) in the US Corn Belt with agronomic benefits.

In short, the limitations to the scalability of ERW are controlled by the scenarios in which it is implemented. Some mineral and rock sources are widely available and can be applied close to the source site, which reduces transportation costs. The most favourable is the use of mine waste tailings being applied on site, which avoids the need for comminution as well as transportation.

scalable, and long-term sustainable removals through atmospheric CO₂ conversion into stable carbonate forms.

David Mine (Galicia, Spain): Field trials at David mine (NW Spain) operated by PASEK MINERALES S.A.U. focus on the CDR efficiency of dunite waste produced in the quarry, compared with artificial soil and biochar synergies for maximizing CO₂ capture and sequestration under a mild oceanic climate. Artificial soils produced by EDAFOTEC S.L. contain bio-stabilized residues and construction/demolition wastes enhancing CO₂ capture, whereas biochar produced by IBERO MASSA FLORESTAL S.A. promotes stable carbon storage and other co-benefits in soil properties.

The field trial parcels configuration is the following (Figure 3):

- ❖ Plot 1: Artificial Soil
- ❖ Plot 2: Artificial Soil and biochar
- ❖ Plot 3: Artificial Soil with dunite
- ❖ Plot 4: Artificial Soil, biochar, and dunite
- ❖ Plot 5: ERW (dunite), vegetation
- ❖ Plot 6: ERW (dunite) *control plot*

EW PILOTS WITHIN THE C-SINK PROJECT

The C-SINK project investigates ERW as a CDR technology through two distinct field trials in Spain (David mine) and Finland (Kevitsa mine), where Monitoring, Reporting, and Verification (MRV) is carried out in situ within active mine sites. Both trials test MRV under real, open-system conditions, focusing on transparent,

Various soil variables, including soil carbon in different chemical forms, are monitored over 24 months in the six experimental plots, including the control and a vegetated plot. Unmanned Aerial Vehicle Remote Sensing (UAV-RS) technologies will be utilized to establish correlations between chemical measurements of different organic carbon fractions and multispectral images acquired. The data collected during

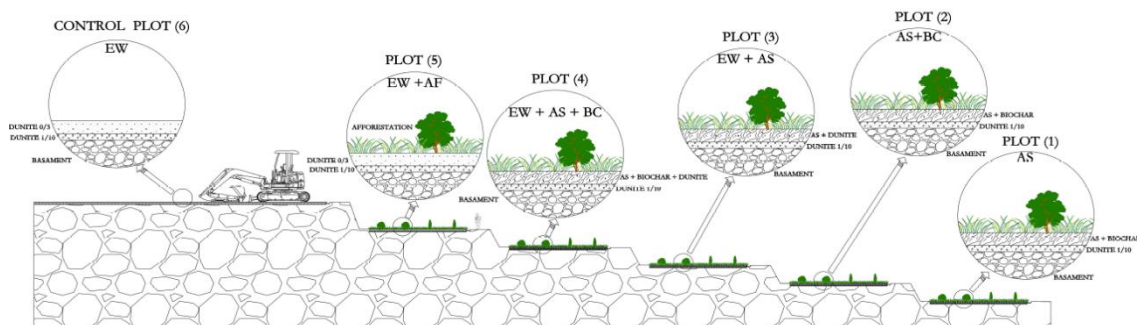


Figure 3. C-SINK field trial set up at David mine in Spain (PASEK MINERALES S.A.U.) in which ERW technology is tested for CDR.

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monitoring will enable the use of artificial soil and ERW under open system conditions. The following physical-chemical parameters are overseen over 24 months:

1. Physical characteristics: Particle size distribution, specific Surface (BET), Bulk density.
2. Chemical characteristics: pH in water, mineralogical analysis (X-ray diffraction), electrical conductivity (EC), chemistry analysis includes trace elements such as As, B, Ca, Cd, Cl, Cr, Cu, Fe, Hg, K, Mg, Mn, Mo, Ni, Pb, S, Se and Zn.
3. Specific carbon analyses: Total inorganic carbon, stable isotopes of C and O with an isotope ratio mass spectrometer (IRMS), inorganic carbon evaluation (DRX, Microscopy, etc.), total Soil Organic carbon (SOC) fractioning of labile and stable C-pools, remote sensing evaluation of organic carbon evolution using UAV (drones) and multispectral.

Kevitsa Mine (Sodankylä, Finland): At Kevitsa, an open-pit nickel, copper, gold, platinum, and palladium mine (N Finland) operated by BOLIDEN AB, field trials focus on the carbonation potential of ultramafic waste rocks and tailings under arctic conditions. An experimental cell is constructed on the west side of the Kevitsa tailings storage facility (TSF).

Figure 4 shows the cross-sectional view of the test cell design. The test cell is placed topographically above the level of tailings placement within the TSF and is constructed with ~2m berm/bund using mine waste rock. The cell is filled with low-sulfur beach tailings sourced from the tailings in situ at the existing TSF.

The tailings material is composed of Mg- and Ca-bearing silicate minerals that capture CO₂ due to the dissolution of reactive silicate minerals to precipitate secondary carbonate minerals. The cell is instrumented with monitoring ports that contain pH, temperature, moisture content/electric conductivity (EC), O₂, and CO₂ probes and sensors at various depths. A gas flux box is placed on top of the cell tailings to monitor O₂ and CO₂ levels at the surface of the tailings. A drain coil is placed at the base to collect leachate for chemical analysis. Additionally, a control monitoring port, dug in the moraine ground, is also instrumented with the same sensors in the tailings test cell to produce data for comparative analysis with the results from the tailings test cell. Key parameters to quantify CDR at Kevitsa mine are:

- ❖ Alkalinity (pH sensor)
- ❖ Gas fluxes (O₂ & CO₂ sensors)
- ❖ Electrical conductivity (EC sensor)

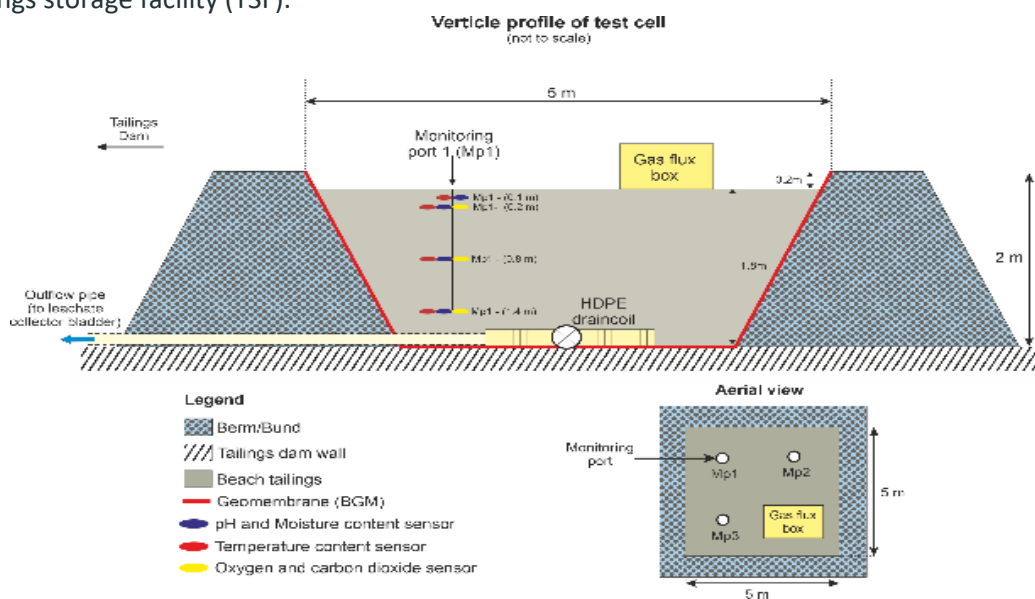


Figure 4. Cell design and setup of the ERW field trial at Kevitsa mine in Finland (BOLIDEN AB), containing a monitoring port and sensors at various depths.



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- ❖ Climate (weather station on site)
- ❖ Dissolved inorganic carbon (DIC) from leachate
- ❖ Major and trace elements (XRF & ICP-MS) – from leachate.

POTENTIAL RISKS

ERW could have some barriers or possible problematic side effects, which do not allow its scaling and should be solved. Some of these were discussed in a range of studies (Hartmann et al., 2013; Strefler et al., 2018; Reershemius, et al., 2023; Samaniego et al., 2023; Vandeginste et al., 2024) and are summarised below:

- ❖ Dust generation due to fine particulate pollution
- ❖ Nickel and chromium accumulation and its release into aquatic and marine systems during dissolution.
- ❖ Change in pH of soils and surface waters (streams, rivers, lakes), affecting terrestrial and aquatic ecosystems.
- ❖ Change in Si concentration of surface waters, affecting ecosystems via altered nutrient ratios
- ❖ Environmental costs of up to three orders of magnitude increase in olivine mining, globally.

CO-BENEFITS

Previous studies (Schuiling & Krijgsman, 2006; Hartmann et al., 2013; Reershemius, et al., 2023) suggested that ERW as CDR-T has potential advantages and co-benefits, such as:

- ❖ A low technological barrier to implementation at scale.
 - ❖ Long-term (>1000 years) storage of carbon compared to organic reservoirs.
 - ❖ Increasing pH of ocean waters, counteracting CO₂-induced acidification
- a) Supply of Si to coastal oceans. May counteract Si limitation and decrease harmful algal blooms.
- b) It may act as “ocean fertilization” to enhance the sequestration of atmospheric CO₂ through the organic carbon biological pump.

- ❖ Supply of Si and other nutrients (principally Fe, Mn, P, K) to terrestrial ecosystems.

a) May increase terrestrial productivity and lead to greater sequestration of CO₂ in terrestrial biomass.

b) May increase crop production, providing additional income for farmers through CO₂ certificate trading and deacidification of soils where ERW feedstocks such as basalt rock can fill the same role as agricultural lime (currently a net source of CO₂ to the atmosphere).

- ❖ Several recent advances make the upscaling of ERW more likely through mechanistic modelling of weathering reactions in agricultural soils and modelling of hydrology affects ERW deployment.

- ❖ Laboratory experiments tracking the uptake of nutrients by plants and feedstock dissolution rates.

Finally, Eufrazio et al. (2022) indicated that ERW is competitive with other large-scale CDR strategies in terms of energy and water demands. More precisely, ERW has potential co-benefits for improved food and soil security and reduced ocean acidification (Beerling et al., 2020) (Smet et al., 2021).

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