

# Enhanced rock weathering in the European Union: Certification, monitoring and governance requirements for responsible carbon dioxide removal

Behrouz Gholamahmadi<sup>1,2,✉</sup>

<sup>1</sup>Department of Research and Development, Ibero Massa Florestal S.A., Ul, Oliveira de Azeméis 3720-584, Portugal

<sup>2</sup>Centre for Environmental and Marine Studies (CESAM), University of Aveiro, Aveiro 3810-193, Portugal

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## ABSTRACT

Enhanced rock weathering (ERW) is moving from geochemical theory into agricultural, commercial, and regulatory practice. This Perspective argues that ERW should enter the European Union carbon-removal portfolio as a promising but conditional soil–climate practice, rather than as a ready-made carbon-credit product. Although silicate weathering can generate durable carbon dioxide removal (CDR), certification remains complicated by time lags, downstream carbon and alkalinity losses, lifecycle emissions, feedstock and site suitability, environmental challenges and uncertainty in field-scale quantification. The emerging EU Carbon Removals and Carbon Farming Certification Framework provides an opportunity to establish an ERW-specific methodology before large-scale crediting occurs. This work proposes that certification distinguish potential from certifiable CDR, combine empirical near-field measurements with conservative modelling of downstream processes, account explicitly for lifecycle emissions and uncertainty, and integrate feedstock, site-suitability and no-harm safeguards. The Common Agricultural Policy (CAP) and soil-health policy can complement certification by supporting monitored deployment where tonne-for-tonne crediting remains premature.

## KEYWORDS

Enhanced rock weathering (ERW), carbon dioxide removal (CDR), soil health, monitoring, reporting and verification (MRV), climate governance, EU policy.

## 1 ERW science, deployment and the EU policy window

Enhanced rock weathering (ERW) is one of the few carbon dioxide removal (CDR) approaches that can, in principle, operate within existing agricultural logistics. Crushed silicate rocks such as basalt are spread on soil, where weathering reactions release base cations and generate dissolved inorganic carbon, particularly bicarbonate, that may be transported through soil water, groundwater, rivers and ultimately the ocean<sup>[1,2]</sup>. This makes ERW attractive for Europe: it appears compatible with agricultural land use, it can use machinery already familiar to farmers, and it links climate mitigation with soil management rather than treating land only as a passive carbon sink.

The difficulty is that ERW is not a simple input–output technology. A tonne of rock dust applied to a field is not automatically a tonne of durable CDR. The timing and magnitude of removal depend on mineralogy, particle size, soil pH, water flux, climate, plant and microbial activity, hydrological connectivity and downstream biogeochemical losses<sup>[1,3]</sup>. The policy challenge is therefore clear: if an ERW methodology permits certified units to be issued before net removal is sufficiently verified, subsequent carbon-market claims could outpace the evidence. If regulation is too slow, Europe may miss a strategic opportunity to shape a credible, science-led market before weaker voluntary standards dominate.

This Perspective takes a deliberately narrow position. ERW

should be developed in the European Union as a conditional soil–climate practice, not as an immediately mature carbon-credit commodity. The question for EU policy is not simply how to incentivise ERW, but how to distinguish three claims that are often merged: first, the geochemical claim that silicate weathering can remove CO<sub>2</sub>; second, the agronomic claim that rock dust may improve soil conditions; and third, the market claim that a quantified unit of durable CDR has occurred. Each claim requires a different evidentiary threshold. This distinction between geochemical potential, agronomic value and certifiable carbon removal is rooted in the biogeochemical characteristics of ERW itself. Although the underlying weathering reactions are well established, translating mineral dissolution into quantified and durable atmospheric CO<sub>2</sub> removal remains considerably more complex.

The scientific case for ERW rests on established weathering chemistry. Silicate minerals consume acidity and release base cations such as calcium and magnesium, which can be charge-balanced by bicarbonate. If that bicarbonate reaches long-term ocean storage, the result can be durable CDR over geological timescales<sup>[4]</sup>. Model- and scenario-based assessments estimate a global ERW potential on croplands in the order of 0.5–2 Gt CO<sub>2</sub> per year by mid-century under favourable assumptions concerning land availability, application rates, weathering conditions and deployment scale<sup>[1,2]</sup>. This range represents scenario-dependent potential rather than readily deployable CDR. This scale explains the rapid scientific, corporate and policy interest.

✉ Address correspondence to Behrouz Gholamahmadi, [behrouzg@ua.pt](mailto:behrouzg@ua.pt)

Yet the same literature also shows why ERW is difficult to certify. First, CDR can be delayed by cation exchange, secondary mineral formation and transport lags. A field may show mineral dissolution without immediate bicarbonate export at the relevant boundary for durable storage. Second, weathering can be driven partly by strong acids associated with nitrogen or sulphur cycling rather than by carbonic acid, weakening the link between cation release and atmospheric CO<sub>2</sub> removal. Third, lifecycle emissions from quarrying, grinding, transport and spreading must be subtracted from gross removal. Fourth, downstream rivers and coastal systems can modify alkalinity, even where initial soil reactions are favourable<sup>[1,5,6]</sup>. These are not reasons to reject ERW. They are reasons to design certification conservatively.

Potential agronomic co-benefits of ERW are strongly context-dependent. Crushed silicate rocks may increase soil pH and nutrient availability and, under some soil and management conditions, reduce nitrous oxide emissions through pH-mediated effects<sup>[7,8]</sup>. Such benefits are more plausible where soil acidity or nutrient constraints exist and should not be assumed across all soils or cropping systems. In calcareous or already alkaline soils, the agronomic rationale may be weaker, and the CDR pathway may differ. Europe is pedologically diverse: Atlantic, Mediterranean, continental and boreal systems differ in rainfall, soil pH, drainage, erosion pressure and crop rotations. An EU methodology, therefore, cannot assume that the same application rate, monitoring system or crediting period is valid across all regions.

These scientific characteristics have direct policy implications. In the European Union, the question is therefore not only whether ERW can contribute to CDR, but whether emerging regulatory frameworks can distinguish potential removal from sufficiently evidenced and certifiable removal.

The EU now has a rare opportunity to govern ERW before it becomes locked into fragmented voluntary-market practice. Regulation (EU) 2024/3012 on Carbon Removals and Carbon Farming (CRCF) establishes a Union certification framework for permanent carbon removals, carbon farming and carbon storage in products<sup>[9]</sup>. In February 2026, the European Commission adopted a delegated regulation establishing the first certification methodologies for permanent removals, covering direct air capture with carbon storage, biogenic emissions capture with carbon storage and biochar carbon removal; ERW is not yet covered by a dedicated EU methodology<sup>[10,11]</sup>. Under the CRCF architecture, certification, unit issuance, and market use are distinct steps. A certification body verifies compliance and issues a certificate of compliance, whereas certified units are issued by the relevant certification registry or, once established, by the Union registry, only after a net carbon-removal benefit has been generated and verified; subsequent transfer, purchase or retirement of those units is a separate market step<sup>[9]</sup>. This sequencing matters. It gives policymakers time to avoid copying generic CDR rules into a pathway where the removal signal is spatially diffused, hydrologically mediated and temporally lagged.

The Soil Monitoring Law adds a second policy anchor. Directive (EU) 2025/2360 creates a Union-wide framework for monitoring and assessing soil health and addresses degradation processes such as erosion, compaction, organic carbon loss, biodiversity decline, contamination and soil sealing<sup>[12,13]</sup>. ERW should be connected to this soil-health agenda but not absorbed by it. Soil improvement indicators can support deployment decisions and farmer participation, yet they cannot substitute for CDR verification. A soil may become less acidic or more productive without delivering a certifiable quantity of durable CDR. Conversely, a credible ERW project may need to monitor

hydrological alkalinity export even where visible agronomic benefits are modest.

A third anchor is agricultural regulation. The EU Fertilising Products Regulation governs categories of fertilising products, contaminants, safety and market access for EU fertilising products<sup>[14]</sup>. The Common Agricultural Policy (CAP), especially eco-schemes under the 2023–2027 framework, supports farmers who adopt environmentally and climatically beneficial practices<sup>[15]</sup>. ERW sits between these regimes. It is physically applied like an agricultural amendment, scientifically justified as a CDR intervention, and politically more acceptable if it contributes to soil resilience. The issue is institutional fragmentation: climate authorities may focus on tonnes of CO<sub>2</sub>, agricultural authorities on input safety and farm uptake, and environmental authorities on soil and water impacts. ERW requires a joined-up EU governance design.

## 2 Why ERW is not yet a mature certifiable CDR pathway

First, an ERW methodology under the CRCF should begin with both feedstock and site eligibility. Mineralogical composition, particle-size distribution, neutralising value, weatherability and contaminant concentrations should be characterised before application. Basalt may often be attractive because of its abundance and nutrient content, but not all basalt is equivalent, while ultramafic materials and some industrial alkaline residues may present greater concerns over nickel, chromium or other trace elements. Eligibility should therefore extend beyond contaminant thresholds to the sustainability of sourcing and processing, including quarrying, crushing and grinding, transport distance, energy demand, dust and noise, land disturbance and impacts on mining and other local communities. Site selection and application rates should additionally be matched to baseline soil properties and pH, crop system, water flux and drainage, locally available mineral resources, expected weathering performance and the transport burden of supplying the feedstock. ERW should be prioritised where these factors support credible net CDR without unacceptable soil, water or ecosystem impacts, and avoided or modified where expected removal is small relative to lifecycle emissions, feedstock–site compatibility is poor, or no-harm thresholds cannot be met<sup>[1,16–18]</sup>.

Second, the methodology should define explicitly what constitutes a certifiable unit of ERW-based CDR. Mineral dissolution, cation release, alkalinity generation and bicarbonate export are successive indicators along the removal pathway, but none should automatically be equated with durable atmospheric CO<sub>2</sub> removal. A certifiable unit should represent net additional atmospheric CO<sub>2</sub> removal attributable to the ERW intervention over a defined reporting period, relative to an appropriate counterfactual, after accounting for relevant near-field carbon and alkalinity losses, conservatively constrained downstream losses, time lags and lifecycle emissions (Figure 1)<sup>[17]</sup>. Feedstock dissolution should therefore be treated as the generation of potential CDR rather than the endpoint of certification. Feedstock properties and application rates should be directly documented, while field measurements should empirically constrain feedstock dissolution and carbon or alkalinity mobilisation and export within the near-field zone. Subsequent transport, transformations and losses through groundwater, rivers and other far-field reservoirs can reasonably be constrained using validated reactive-transport or geochemical models, with project lifecycle emissions quantified separately (Figure 1)<sup>[17]</sup>.

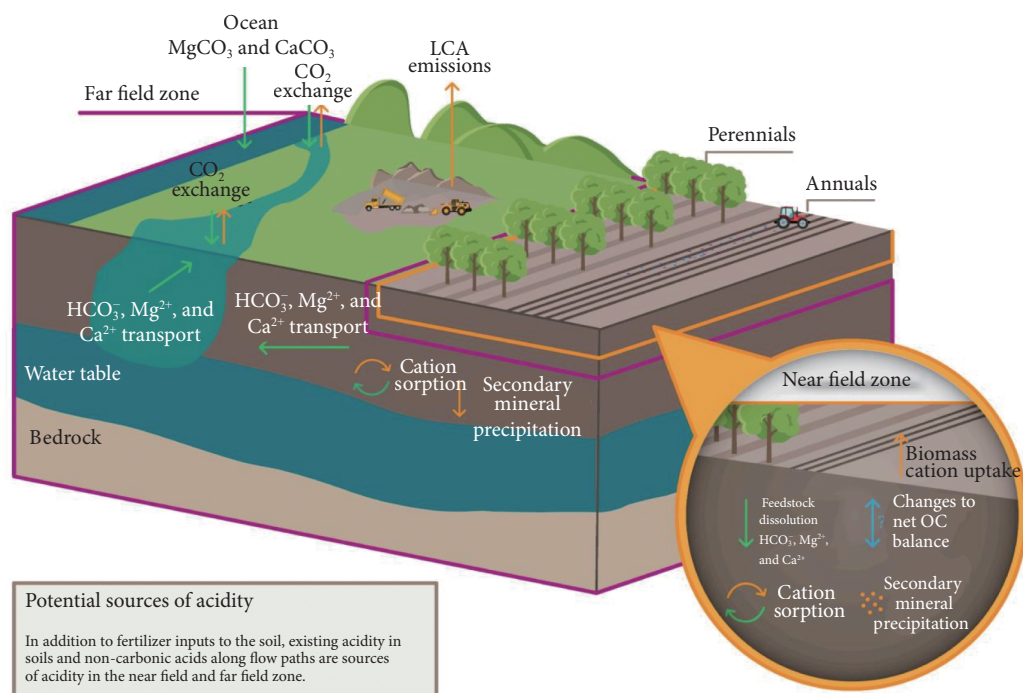


**Fig. 1** Accounting boundary for carbon dioxide removal through enhanced rock weathering. The Near-Field Zone encompasses the amended soil system in which feedstock dissolution, carbon and alkalinity fluxes, cation sinks and other relevant processes can be directly constrained. The Far-Field Zone encompasses subsequent transport through deeper soils, groundwater, surface waters and, where relevant, the ocean, where carbon losses and durable storage must be constrained. Lifecycle emissions are accounted for separately. Adapted from Ref. [17], under the Creative Commons Attribution 4.0 International (CC BY 4.0) license.

The same evidentiary standard need not imply the same measurement density at every farm. The monitoring, reporting and verification (MRV) intensity should be proportionate to project scale, site heterogeneity and the quantity of CDR claimed: early demonstration sites and representative subplots can support denser direct measurements, while statistically designed sampling, shared monitoring infrastructure and independently validated models can progressively reduce per-hectare monitoring burdens across larger or aggregated deployments<sup>[17]</sup>. This proportional approach is particularly important for small and geographically dispersed farms, for which high fixed MRV costs could otherwise become a barrier to participation. Measurement, sampling and model uncertainties should be propagated into the net-CDR estimate and reflected conservatively in unit issuance, for example through uncertainty discounts or lower-bound estimates; where the resulting removal cannot be adequately bounded, the corresponding certified unit should not yet be issued.

Third, unit issuance should be ex post, staged and explicitly lag-aware. Consistent with the CRCF, certified units should be issued only after a net carbon-removal benefit has been generated and verified<sup>[9]</sup>. For ERW, neither rock application nor mineral dissolution alone should trigger unit issuance. Where near-field measurements demonstrate additional removal but transfer towards durable far-field storage remains delayed, only the fraction for which downstream losses and storage durability can be conservatively bounded should be eligible for issuance during that reporting period; the unresolved fraction should remain unissued until subsequent monitoring and validated modelling reduce the uncertainty<sup>[17]</sup>. Substantial time lags should therefore translate into delayed or partial issuance rather than ex ante crediting. Where uncertainty remains high, pay-for-practice support through the Common Agricultural Policy (CAP) or

national soil programmes may be more appropriate than tonne-for-tonne CDR crediting.

Fourth, the methodology should separate CDR claims from co-benefit claims. Soil pH improvement, nutrient substitution, yield response, reduced fertiliser demand, erosion reduction or resilience to drought may justify public support, but they are not equivalent to verified CO<sub>2</sub> removal. The same applies to potential reductions in nitrous oxide emissions. These should be reported in separate modules, with different baselines and uncertainty treatment.

Fifth, social acceptance must be designed into ERW governance. Public understanding of CDR and ERW remains limited, and local acceptance is likely to depend on visible farmer benefit, trust in feedstock safety, transparent monitoring and credible safeguards for water, biodiversity and mining impacts<sup>[1,19]</sup>. In Europe, where farmer protests and regulatory fatigue have already shaped agricultural policy debates, ERW cannot be presented as another top-down obligation. It must be offered as a monitored, optional and locally justified practice, with benefits and liabilities clearly allocated. The principal challenges associated with ERW and the corresponding monitoring, management and certification safeguards are summarised in Table 1.

### 3 Governance and certification priorities for responsible ERW

Long-term field evidence is particularly important because weathering rates, CDR time lags and secondary mineral formation evolve over multi-year timescales. Accordingly, Beerling et al.<sup>[1]</sup> recommend ERW field trials lasting 10–15 years to resolve these coupled processes and avoid extrapolating long-term performance from short-duration experiments (see Table 2).

**Table 1 Principal challenges and corresponding safeguards for responsible enhanced rock weathering deployment.**

| Main challenge                                               | Monitoring or management safeguard                                                                                                 | Certification implication                                                                                            |
|--------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|
| Uncertain magnitude and timing of CDR                        | Empirical near-field measurements, validated far-field modelling, uncertainty propagation and repeated monitoring                  | Apply conservative uncertainty discounts; delay or partially issue units where downstream removal remains unresolved |
| Trace-element mobilisation and adverse soil or water effects | Feedstock screening, baseline soil and water characterisation, repeated environmental monitoring and predefined no-harm thresholds | Exclude unsafe feedstocks or sites; suspend or modify deployment where thresholds are exceeded                       |
| Lifecycle emissions and upstream environmental burdens       | Account for quarrying, grinding, transport, spreading, energy use and associated emissions within lifecycle assessment             | Deduct lifecycle emissions from net CDR and reject deployment where burdens materially undermine net removal         |
| Feedstock–site or application-rate mismatch                  | Match mineralogy and application rates to soil properties, crop system, hydrology, weathering potential and transport distance     | Restrict deployment to sites where credible net CDR and environmental compatibility can be demonstrated              |
| Social and governance challenges                             | Transparent monitoring, farmer participation, clear allocation of responsibilities and predefined review or stopping rules         | Modify or discontinue deployment where material adverse outcomes, non-compliance or unacceptable local impacts occur |

**Table 2 Policy requirements for responsible enhanced rock weathering deployment in the European Union.**

| Policy action                                                           | Responsible level                                                      | Minimum requirement                                                                                                                                                                                                                             | Reason for inclusion                                                                                                                                                                                   |
|-------------------------------------------------------------------------|------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Create an ERW-specific CRCF methodology                                 | European Commission, expert group and recognised certification schemes | Define eligible feedstocks, accounting boundaries, permanence assumptions, uncertainty discounts, monitoring periods and registry rules.                                                                                                        | ERW has pathway-specific lags and downstream processes that cannot be handled by generic CDR certification.                                                                                            |
| Require cradle-to-grave MRV                                             | Certification bodies, project developers and Member State authorities  | Combine feedstock testing, statistically designed field sampling, targeted soil-water monitoring, validated models and lifecycle emissions accounting, with monitoring intensity proportionate to project scale, heterogeneity and claimed CDR. | Durable CDR depends on carbon and alkalinity transfer beyond the amended topsoil, not merely rock application.                                                                                         |
| Separate certified CDR units from agronomic and soil-health co-benefits | European Commission, CAP authorities and certification schemes         | Report pH, nutrient, yield, N <sub>2</sub> O, erosion and water-quality outcomes in separate modules from carbon-removal units.                                                                                                                 | Co-benefits can justify support but should not inflate CDR claims.                                                                                                                                     |
| Use CAP and national soil programmes for early deployment support       | Member States and CAP managing authorities                             | Support monitored pilots, advisory services and farmer participation without requiring immediate tonne-for-tonne crediting.                                                                                                                     | Practice-based support is more suitable where uncertainty, lag times or MRV costs are still high.                                                                                                      |
| Build an EU long-term field-trial network                               | Horizon Europe, Mission Soil, Joint Research Centre and Member States  | Fund 10- to 15-year trials across Mediterranean, Atlantic, continental and northern systems, with open datasets and common protocols.                                                                                                           | ERW performance depends strongly on soil, climate, hydrology and crop system; decadal trials are needed to resolve weathering kinetics, CDR time lags and secondary mineral formation <sup>[1]</sup> . |
| Adopt feedstock, site-suitability and no-harm safeguards                | DG GROW, DG ENV and Member State regulators                            | Align with fertilising-product and waste rules; require feedstock screening, site-suitability assessment, trace-metal thresholds, environmental monitoring and exclusion of unsafe feedstocks or unsuitable deployment conditions.              | Large-scale ERW will face social and legal barriers if safety is treated as secondary to carbon accounting.                                                                                            |

Note: DG GROW, Directorate-General for Internal Market, Industry, Entrepreneurship and Small and medium-sized enterprises; DG ENV, Directorate-General for Environment.

A conservative EU approach should not be confused with policy paralysis, nor would an EU methodology need to begin from zero. Existing voluntary-market approaches already illustrate different ways of addressing ERW quantification. The Puro.earth methodology incorporates net-removal accounting, project and lifecycle emissions, carbon-loss pathways, monitoring, uncertainty quantification and discounting<sup>[20]</sup>, while Isometric's current protocol requires direct measurement of initial feedstock weathering, allows soil- or porewater-based quantification, recommends an independent secondary validation approach, and explicitly accounts for relevant downstream riverine and marine losses<sup>[21]</sup>. By contrast, Verra has kept development of its proposed

agricultural ERW methodology on hold, citing remaining uncertainties in quantification, durability and field-scale performance<sup>[22]</sup>. These contrasting approaches reinforce the case for adaptive certification: an EU methodology could build on emerging MRV practice while placing feedstock safety, site suitability, transparent uncertainty treatment and conservative unit issuance within a common public regulatory framework.

Europe also has a strategic advantage because the Union already has regulatory infrastructure for product safety, environmental monitoring, agricultural payments and carbon-removal certification. The institutional instruments proposed here are therefore partly EU-specific: the CRCF can provide the

certification architecture, while the Soil Monitoring Law and Common Agricultural Policy can support environmental oversight and farmer participation. The underlying governance principles, however, are not uniquely European. Feedstock safety, site suitability, lifecycle accounting, conservative MRV, explicit treatment of uncertainty and separation of verified CDR from agronomic co-benefits are transferable to ERW governance in other jurisdictions<sup>[1,17]</sup>. Their implementation will necessarily differ with farm structure, climate, soils, mineral resources and regulatory capacity. Within the EU itself, suitable mineral resources are also unevenly distributed among Member States, creating spatial differences in feedstock availability, transport requirements and potential deployment costs<sup>[23]</sup>. An EU methodology that applies these principles transparently could therefore provide a useful reference for emerging ERW frameworks elsewhere without implying that European institutions or monitoring requirements should simply be replicated globally.

## 4 Conclusions

ERW belongs in the European CDR conversation, but it should enter through the front door of evidence-based governance. The strongest policy case for ERW is not that it offers an easy carbon-credit opportunity. It is that ERW may allow Europe to link durable CDR, soil resilience, agricultural transition and rural participation within one carefully monitored practice. That opportunity will be lost if ERW is certified as a simple function of tonnes of rock applied to hectares of land. The EU should therefore develop ERW as a staged, conditional and soil-specific CDR pathway. The priority is an ERW-specific CRCF methodology with cradle-to-grave accounting, feedstock safeguards, lifecycle emissions, uncertainty discounts and explicit treatment of lag times. The second priority is integration with the Soil Monitoring Law, CAP eco-schemes and Mission Soil field infrastructure, so that farmers are supported for monitored soil-climate practice even before full tonne-for-tonne crediting is justified. The third priority is long-term European field evidence. ERW can become a credible part of the EU climate portfolio, but only if certification follows science rather than market pressure.

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## Author contribution statement

Not applicable.

## Data availability

No new datasets were generated or analysed in this manuscript.

## Use of AI statement

During preparation of this work, the author used ChatGPT for language editing, formatting and manuscript-structuring support. The author reviewed and edited the content and takes full responsibility for the final manuscript.

## Declaration of competing interest

The author is an employee of Ibero Massa Florestal S.A., Portugal, but has no competing interests to declare that are relevant to the content of this article.

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**Behrouz Gholamamhadi** received his Ph.D. degree in environmental sciences and engineering from the University of Aveiro, Portugal. He is currently Director of Research and Development and EU Projects Leader at Ibero Massa Florestal S.A. and is affiliated with the Centre for Environmental and Marine Studies (CESAM), University of Aveiro. His research focuses on soil-based climate mitigation and durable carbon dioxide removal,

particularly biochar-based materials and enhanced rock weathering. He integrates evidence synthesis, field-scale biophysical processes and carbon-removal governance, with particular interest in monitoring, certification and the responsible integration of agronomic co-benefits into climate policy.