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Pathways, roundabouts, roadblocks, and shortcuts to safe and sustainable deployment of enhanced rock weathering in agriculture

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1 Introduction

Enhanced rock weathering (ERW), as a negative emissions technology for climate change mitigation, has received far more public, governmental, and academic attention (according to the authors' account of engagement with such actors) in the past year than in the many years since its first mention in the literature. The term ERW was conceived by Beerling (2017), but the field of research referred to as "enhanced weathering" (EW) can see its origins, by this name, at least as far back as the works of Power and Southam (2005) and Lenton and Britton (2006). This opinion piece provides learnings and thoughts from the GeoRewind group at the University of Guelph (Canada) on what we have defined as "pathways," "roundabouts," "roadblocks," and "shortcuts" to the safe and sustainable deployment of ERW in agriculture.

2 Current status of ERW research and deployment

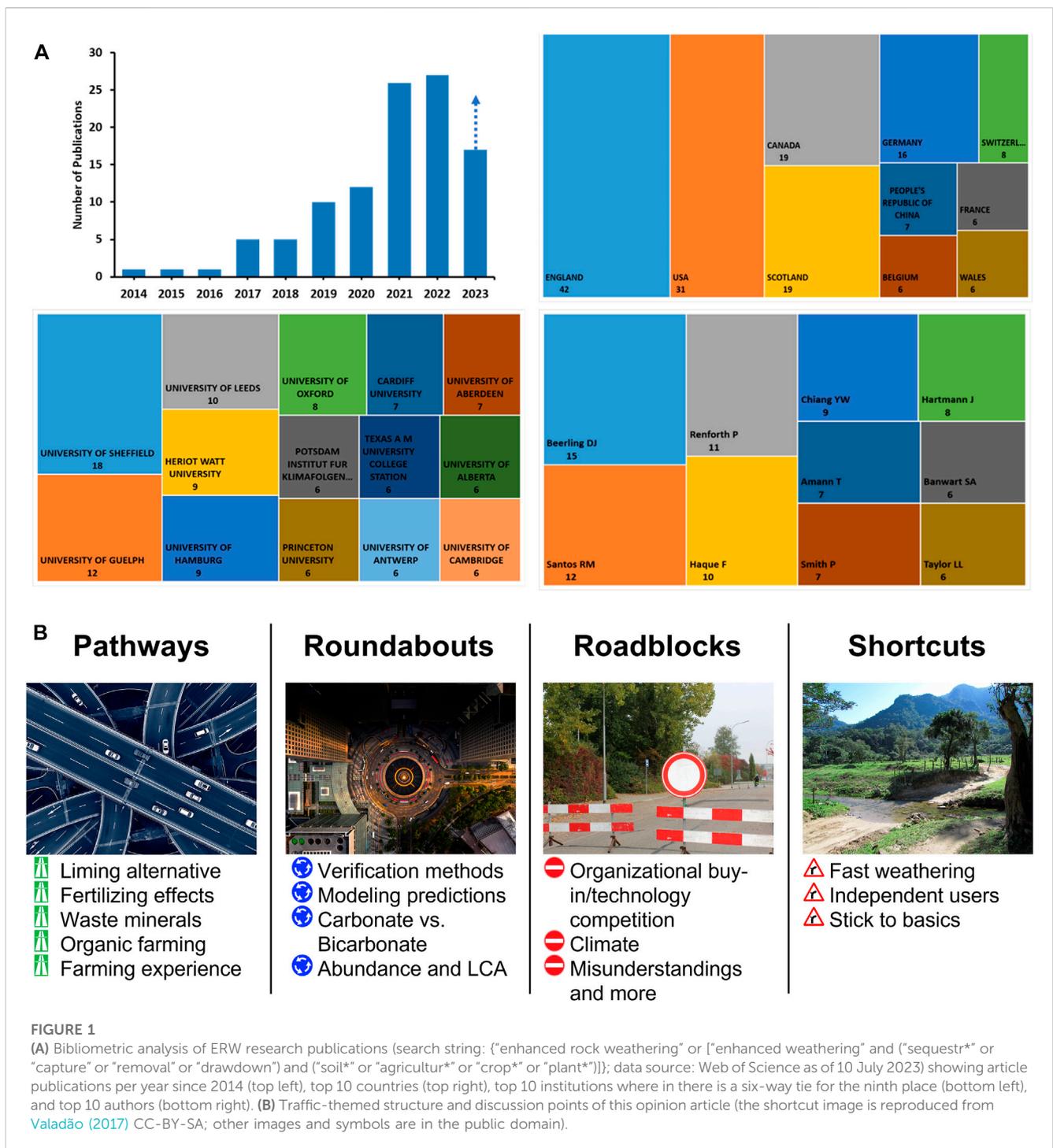
In the academic space, the pace of publications and the diversification of countries and institutions involved in EW research have undoubtedly accelerated in recent years (Figure 1A), but it still feels like this is the tip of the iceberg (e.g., unequal global reach), considering the many lingering questions to be addressed. For example, the carbon removal knowledge gaps listed in the [Frontiersgaps.com](https://frontiersgaps.com) (2023) website include, as of April 2023, questions on: 1) how the choice of mineral feedstock (e.g., virgin vs. residual and basalt vs. other silicates) affects ecosystem co-benefits and/or environmental impacts; 2) how mineral feedstock should be characterized for safe use; 3) what an optimal mineral application (and re-application) rate is and its timing, considering desired carbon sequestration rates, costs, and farming practices; 4) in what ways silicate minerals interact with other soil amendments and with other soil acids; and 5) the longstanding (and at times debatable as in Buckingham et al. (2023) versus West et al. (2023)) geochemistry topic of determining realistic weathering rates under field conditions. Such open questions about the feasibility, practicality, and efficiency of ERW inspire discussions that follow.

Evidence of ERW as a technology moving from the academic side to the deployment side (also known as crossing the so-called "valley of death" of innovation (Ellwood et al., 2022)) includes new companies and business models that are supporting the mineral supply, the

creation and management of monitoring, reporting, and verification (MRV) methodologies, and the issuance of credits for carbon removal/avoidance/offset (André and Valenciano-Salazar, 2022). A highlight of 2022 was the public release of the Puro Standard Enhanced Rock Weathering Methodology (Puro.earth, 2022) to be used in the voluntary carbon markets to enable the issuance of CO₂ removal certificates (CORCs) for ERW activities of certified suppliers. In the same line of thought as Finland-based Puro.earth, US-based VERRA also set out in 2022 to establish its own methodology (VERRA, 2022). US-based CarbonPlan also

released in 2022 a framework to help guide research and MRV efforts on ERW (CarbonPlan, 2022).

On the suppliers' front, several companies that recently emerged have made critical strides. UK-based UNDO celebrated in 2022 its first commercial-scale deployment of basalt (UNDO, 2022), Ireland-based Silicate Carbon was a Shell GameChanger Winner in the THRIVE | Shell Climate-Smart Agriculture Challenge (THRIVE, 2023), and US-based Lithos Carbon has reportedly spread over 11,000 imperial tons of basalt (Wire, 2022). Here, it is notable that these companies have been founded by, or have close relationships



with, the most active academic research groups on ERW, which speaks of the need for a scientific direction on the deployment of ERW, given the aforementioned lingering questions.

3 Discussion of pathways, roundabouts, roadblocks, and shortcuts to safe and sustainable deployment of ERW in agriculture

The GeoRewind team has categorized over 5 years of ERW experiences into the following traffic-inspired (Figure 1B) subsections. To be clear, these are not meant to be comprehensive or exhaustive discussions but food for thought for future ERW efforts.

3.1 Pathways for ERW

Pathways are low-resistance directions in ERW research and deployment that help accelerate hypothesis testing, knowledge accumulation, and the creation of feasible and trustable practices.

3.1.1 Liming alternative

The common use of liming agents in agriculture (wherein liming with limestone/dolomite is typically a net CO₂ emitter (West and McBride, 2005)) is the most direct path for silicate amendments, considering the available supply chain, equipment for spreading, budget for soil amendment, scheduling opportunity, and long-term experience with mineral amendments. Notably, there are clear grower recommendations on the amendment rate of liming agents based on their liming index (Reid et al., 2006), yet the liming index of silicate amendments is unknown, and available studies on the use of silicates as liming agents are often inconclusive about their liming effects and effects on soil carbon (Amoakwah et al., 2023), wherein overliming with silicates (Yan et al., 2023) can cause the same short-term loss of soil organic carbon as for conventional liming (Paradelo et al., 2015). This calls for measured amendment approaches when considering the need for a sufficient silicate amendment to enable MRV and correct dosage to maximize agronomic benefits and total soil carbon storage.

3.1.2 Fertilizing effects

The field of soil remineralization is being developed alongside the technology of ERW and has a longer existence, considering that rock dusts have historically been used worldwide as a locally available low-cost fertilizing amendment (van Straaten, 2007). Many silicate rocks contain appreciable amounts of plant nutrients such as P and K, which can be mobilized during weathering; hence, their use to reduce (at least partially) the use of artificial fertilizers can have additional emission reduction consequences. An often-overlooked non-essential plant nutrient is silica, which is also released in a reactive form (colloidal silica or silicic acid) during weathering and can be beneficial for crops that take up silica for tissue strength (Jariwala et al., 2022; Swoboda et al., 2022).

3.1.3 Waste minerals

A continued concern about the scalability of ERW is the sourcing of suitable minerals and the added environmental impact of new mining operations. There are global stockpiles of mine waste, from quarrying activities, ore mining activities, and metallurgical activities, that have weathering potential and suitable safe composition (Paulo et al., 2021), and those are low-hanging fruits, apart from possible regulatory barriers on waste use in food production, to accelerate ERW deployment.

3.1.4 Organic farming

Despite representing a small fraction of global farming operations, organic farming calls for the use of natural soil amendments. Silicate minerals, as liming agents, fertilizing agents, or solely for carbon sequestration, can qualify for organic use. For example, wollastonite used in the GeoRewind work is organic-certified (Organic Materials Review Institute, 2015).

3.1.5 Farming experience

Many farmers are used to liming; hence, there is a low barrier to entry for ERW if the same conventional logistics are used to deliver and spread minerals. Notably, farming experience should trump scientific advice that, at times, propose very large amendment rates (Kelland et al., 2020). According to the Ontario Agricultural College Dean Prof. Rene Van Acker, “If the technology does not take into account the practical reality of farming, that’s a big mistake” (Grip Workshop, 2023).

3.2 Roundabouts of ERW

Roundabouts are topics that generate certain levels of uncertainty and that can lead to taking a better path when an evidence-based decision is made. On the spectrum of technology development, they consume time and energy but often help thoughts mature and become well-grounded.

3.2.1 Verification methods

It remains unclear if ERW verification should rely on soil water analysis (e.g., for alkalinity, electrical conductivity, isotope, or trace metal analysis), soil solid analysis (e.g., calcimetry, thermogravimetry, X-ray diffraction, and X-ray fluorescence), gas analysis (e.g., soil P_{CO2} and eddy covariance), or even remote sensing (Almaraz et al., 2022). Scientifically, an all-of-the-above approach is useful for building confidence in the mechanisms of ERW and the fate of weathering products and residues, but practically, it remains to be determined what a feasible, scalable, and equitable form of verifying ERW rates and extent is. Eventually, as with other farming practices, ERW may become a guideline-based practice rather than verification-based technology.

3.2.2 Modeling predictions (global and site-specific)

Efforts have been made to model ERW from the scale of a single mineral grain (Georgakopoulos et al., 2016) to a finite portion of soil (column or a field) (Kelland et al., 2020), or to a watershed and beyond (Zhang et al., 2022). All of these have drawbacks, limitations, and uncertainties. Yet modeling is the backbone of MRV

methodologies. As with verification, distinctions are needed for what models are meant for scientific use and what models serve to constrain carbon sequestration estimates (i.e., net CO₂ removal after accounting for carbonate precipitation (partial or complete), CO₂ off-gassing, loss of alkaline earth metals to sorption and plant uptake, etc.) and be connected to carbon markets.

3.2.3 Carbonate vs. bicarbonate

Some studies have assumed that solid carbonates are the products of ERW (Manning et al., 2013; Haque et al., 2020), and some have assumed that soluble bicarbonates are the products (Amann and Hartmann, 2022; Buckingham et al., 2022). Either can be, and at any point in time, they depend on the soil, climate, soil saturation, and other factors (Khalidy et al., 2022). The carbonate assumption is conservative (and geologically long-term), while the bicarbonate assumption is maximal (and geologically short-term). It, thus, remains an MRV uncertainty as to what alkaline earth metal-to-CO₂ ratio to use in the carbon accounting of ERW. An equitable solution may be to use a constant global value of such ratios (within reason as to locations/conditions that make sense for ERW) as it is not at the farmer's control if the ratio in one land is lower than in another, yet farmers incur similar costs for silicate spreading.

3.2.4 Abundance and LCA

The availability of abundant minerals regionally for any given point of application is intricately tied to the life cycle carbon footprint of an ERW implementation (Eufrazio et al., 2022). Mineral reserves of suitable silicates for ERW are not well-recorded as geological surveys normally focus on ores of commercial value for other applications. As such, a renewed consideration of minerals stocks is needed to inform LCA models of ERW deployment in different regions of the world. Some efforts have been made for mine tailings (Bullock et al., 2021; Bullock et al., 2022).

3.3 Roadblocks to ERW

Roadblocks put a stop to a certain research direction or idea. However, roadblocks eventually clear, so they are instances where unforeseen work is needed to overcome deployment barriers.

3.3.1 Organizational buy-in/technology competition

Government agencies and industrial organizations (e.g., grower associations) have been slow to notice and take up interest in ERW. Examples of this include the absence of ERW mention in agricultural funding calls, the usage of the term “soil carbon sequestration” to signify only those approaches that lead to organic carbon accumulation (Bai and Cotrufo, 2022), and the lack of ERW research occurring within such agencies and organizations or with involvement of their members (from the bibliometric data on Figure 1A, the few exceptions include Haque et al. (2019), Gomez-Casanovas et al. (2021)). This shows that academic groups should perform more of what is known as “knowledge translation and transfer,” “getting research into practice,” and “extension research” (Grip workshop, 2023).

3.3.2 Climate

Conceptual reviews on ERW have largely told a story that ERW is best suited for deployment in warmer regions, at times termed the “Global South” (Institute for Carbon Removal Law and Policy, 2023), in view of higher weathering rates and more acidic soils (Taylor et al., 2016). This has led some studies to omit the deployment of ERW in the vast farmland regions of wealthier nations located in colder or drier climates, such as Canada and the Northern Plains of the US (Hicks et al., 2022). Considering mineral sources and financing resources, ERW should be pursued in most regions of the world as a means to accelerate the development of logistics, guidelines, regulations, and MRV methodologies, and to identify risks and limits before it is deployed at large scales in regions where impacts may be less likely to be studied.

3.3.3 Misunderstandings and more

Historically, certain misunderstandings and disagreements have either slowed the progress on ERW until additional studies could move the science forward, or created conditions that could discourage large-scale ERW adoption. Examples include the following:

- (i) In the early days of ERW research, it was posed that silicic acid accumulation in natural waters would hinder the weathering reaction progress based on the principles of reaction equilibrium (Köhler et al., 2011), but a debate with Schuiling et al. (2011) showed that silicon removal via the formation of solid phases and biological sinks is the more plausible mechanism, and one that remains well-grounded by experimental observations and is used in reactive ERW models.
- (ii) It has been suggested that metal leaching and accumulation can be significant risks of ERW, but one study that posed this concern was focused on the use of metallurgical slags (Choi et al., 2021), while others have spoken of Ni and Cr present in olivine (Dupla et al., 2023). Yet, many of the minerals tested in the ERW field and laboratory experiments are free (i.e., below regulated levels) of metals of concern (Dudhaiya et al., 2019; Lewis et al., 2021). Evidently, this is a point that deserves caution, accounting, and ecotoxicity assessment (Vienne et al., 2022; Vink and Knops, 2023) but not a technological roadblock.
- (iii) A recent study (Buckingham et al., 2022) suggested that a large extent of the UK's croplands is too dry for ERW deployment, and hence, estimates for carbon drawdown potential for the UK should be lower than earlier estimates. West et al. (2023) suggested that the study's conclusions were affected by large evapotranspiration from the rooftop soil columns and the omission of pedogenic carbonate detection (as also pointed to by Ali and Santos (2023)). In response, Buckingham et al. (2023) refuted these assertions but did not address some specific concerns raised by West et al. (2023) about evapotranspiration and did not provide calcimetry data on the soils to accurately quantify soil inorganic carbon accumulation. This exchange exemplifies how inconsistencies in experimental design and the lack of more distributed studies can act as roadblocks when the reported data are extrapolated to making general recommendations, calling for careful attention to experimental design and data processing.

3.4 Shortcuts for ERW

Shortcuts serve many purposes: they shorten the journey; they help circumvent roadblocks; and when in the form of a bridge, they help overcome a gap.

3.4.1 Fast weathering

A couple of ways to overcome roadblocks 3.3.1 and 3.3.2 have been: 1) to use faster-weathering minerals (such as wollastonite, slags, or concrete residues) (Renforth et al., 2009) and 2) to perform experiments in more amiable climates (e.g., Brazil and Malaysia) (Silva et al., 2021; Larkin et al., 2022). Such strategies have worked and should remain a key means of accelerating ERW understanding, deployment, and risk and impact analysis. However, shortcuts can also create traffic jams, themselves becoming roadblocks (e.g., exclusive focus on 2), so other pathways should be explored alongside.

3.4.2 Independent users

Farmers have used rock dust and other mineral amendments for decades and, in some cases, have used the same rocks and minerals being tested for ERW. An evident shortcut to generating more robust multi-year data, previewing long-term impacts, and looking for evidence of past weathering is to visit these locations to collect soil and water samples for study. Few publications have touched on this strategy (Haque et al., 2020; Taylor et al., 2021), possibly due to the challenge of forensic MRV versus forward-looking MRV, so opportunities remain.

3.4.3 Stick to basics

A closing thought on the complexities of MRV is whether there is the absolute need for such complexities and to what extent. It is inherently difficult to quantify the ERW rate and extent under field conditions, considering the workload involved in collecting representative soils, waters (and even gases), and the uncertainties involved in their analyses and data interpretation. Sticking to basics is a reminder that at a very fundamental level, ERW should work on most croplands, to an extent, as it consists of exposing silicate minerals to conditions in which they are likely to weather much faster than if left to natural geological processes. The following questions are raised:

- Should farmers be rewarded for participating in ERW based on mineral application (respecting agronomic limits that farmers should self-impose), or based on carbon drawdown? One of these is bound to be more equitable and the other more profitable.
- Is the complexity of MRV based on physical sampling worth it, or are models and even simpler guidelines sufficient to regulate the practice of ERW and issue carbon certificates?

- At what point does sampling-based MRV give way to trust in ERW as a conventional agricultural practice: 1) when climate change models signal that ERW is doing its job; 2) when the rest of the economy is sufficiently decarbonized; 3) or will MRV become such a profitable endeavor that it outlives its need?

It is important to answer these questions from the point of view of the global and multi-decadal potential that ERW has and not only what scientists and early startups need to confirm the science. Agriculture has been historically based on trust in science to a great extent, so it remains to be seen if ERW will find its place as a mainstream agricultural technology in addition to being a geoscience technology.

Author contributions

RS, FH, and YC contributed to the conception and design of the study. RS wrote the first draft of the manuscript. FA, HJ, and RK wrote sections of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

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