Received: 26 July 2021 | Revised: 4 October 2021 | Accepted: 10 November 2021

DOI: 10.1111/gcb.15993

Global Change Biology WILEY

OPINION

Is the climate change mitigation effect of enhanced silicate weathering governed by biological processes?

Sara Vicca[1] | Daniel S. Goll[2] | Mathilde Hagens[3] | Jens Hartmann[4] | Ivan A. Janssens[1] | Anna Neubeck[5] | Josep Peñuelas[6,7] | Sílvia Poblador[1] | Jet Rijnders[1] | Jordi Sardans[6,7] | Eric Struyf[1] | Philipp Swoboda[8] | Jan Willem van Groenigen[9] | Arthur Vienne[1] | Erik Verbruggen[1]

[1]Plants and Ecosystems (PLECO), Biology Department, University of Antwerp, Wilrijk, Belgium

[2]CEA-CNRS-UVSQ, LSCE/IPSL, Université Paris Saclay, Gif sur Yvette, France

[3]Soil Chemistry and Chemical Soil Quality, Environmental Sciences, Wageningen University and Research, Wageningen, The Netherlands

[4]Institute for Geology, Center for Earth System Research and Sustainability, University of Hamburg, Hamburg, Germany

[5]Department of Earth sciences, Uppsala University, Uppsala, Sweden

[6]CSIC, Global Ecology CREAF- CSIC-UAB, Barcelona, Spain

[7]CREAF, Barcelona, Spain

[8]International Centre for Sustainable Development, Bonn-Rhein-Sieg University of Applied Sciences, Sankt Augustin, Germany

[9]Soil Biology Group, Wageningen University and Research, Wageningen, The Netherlands

Correspondence
Sara Vicca, Plants and Ecosystems (PLECO), Biology Department, University of Antwerp, Universiteitsplein 1, 2610 Wilrijk, Belgium.
Email: sara.vicca@uantwerpen.be

Funding information
Fundación Ramón Areces; Catalan Government, Grant/Award Number: SGR 2017-1005; Universiteit Antwerpen; Spanish Government, Grant/Award Number: CGL2016-79835-P; H2020 Future and Emerging Technologies, Grant/Award Number: 964545 — BAM; Agence Nationale de la Recherche, Grant/Award Number: ANR-16-CONV-0003; Fonds Wetenschappelijk Onderzoek

Abstract

A number of negative emission technologies (NETs) have been proposed to actively remove CO_2 from the atmosphere, with enhanced silicate weathering (ESW) as a relatively new NET with considerable climate change mitigation potential. Models calibrated to ESW rates in lab experiments estimate the global potential for inorganic carbon sequestration by ESW at about 0.5–5 Gt CO_2 year^{-1}, suggesting ESW could be an important component of the future NETs mix. In real soils, however, weathering rates may differ strongly from lab conditions. Research on natural weathering has shown that biota such as plants, microbes, and macro-invertebrates can strongly affect weathering rates, but biotic effects were excluded from most ESW lab assessments. Moreover, ESW may alter soil organic carbon sequestration and greenhouse gas emissions by influencing physicochemical and biological processes, which holds the potential to perpetuate even larger negative emissions. Here, we argue that it is likely that the climate change mitigation effect of ESW will be governed by biological processes, emphasizing the need to put these processes on the agenda of this emerging research field.

KEYWORDS
carbon sequestration, enhanced weathering, greenhouse gas emissions, negative emissions, soil biota

1 | INTRODUCTION

Conventional climate change mitigation alone will not be able to stabilize atmospheric carbon dioxide (CO_2) concentrations at a level compatible with the "well below 2°C warming" limit of the United Nations' Paris Agreement (UNFCCC, 2015). Safe and scalable negative emission technologies (NETs), which actively remove CO_2 from the atmosphere and ensure long-term carbon (C) sequestration, will be needed to meet this goal (Gasser et al., 2015). Depending on how fast greenhouse gas (GHG) emissions are reduced, 100–1000 Gt CO_2 will have to be removed from the atmosphere by 2100 (IPCC, 2018, 2021; Psarras et al., 2017; Rockström et al., 2017). Decarbonization roadmaps show that NETs must be deployed quickly and at a large scale: CO_2 removal would need to reach about 5 Gt CO_2 $year^{-1}$ by 2050, and increase further to about 10 Gt CO_2 $year^{-1}$ between 2050 and 2100 (Obersteiner et al., 2018; Rockström et al., 2017). Fast progress in achieving cost-efficient NETs is needed if we are to meet the Paris Agreement's ambitions (Hilaire et al., 2019).

Enhanced silicate weathering (ESW) is a relatively new, low-tech NET with considerable climate change mitigation potential (Beerling et al., 2020; Fuss et al., 2018; Goll et al., 2021; Köhler et al., 2010; Strefler et al., 2018). The mechanism of CO_2 removal by ESW is based on speeding up the natural process of silicate weathering. The principle of ESW is the reaction of silicate grains with CO_2 and water to form bicarbonates which can either leach out of the soil into the groundwater, rivers, and eventually the ocean, or precipitate in the soil, forming pedogenic carbonates (Figure 1). The latter reduces short-term C storage approximately by half, but in both cases, C is stored for hundreds of years and longer (Hartmann et al., 2013; Köhler et al., 2010).

The proof of principle that silicate weathering draws down atmospheric CO_2 can be found in the geological record, where the negative temperature-weathering feedback is believed to have stabilized Earth's climate (Berner, 2004; Walker et al., 1981). Increasing CO_2 concentrations raise temperatures and increase rainfall, thereby accelerating silicate weathering rates and atmospheric CO_2 removal, hence, slightly mitigating the warming trend by about 0.04 $W\,m^{-2}\,K^{-1}$ (Goll et al., 2014). The idea of ESW is to increase C sequestration through mineral weathering by actively amending soils with finely ground, fast-weathering silicates such as basalt (Hartmann et al., 2013; Schuiling & Krijgsman, 2006). Soil amendment with basalt, an abundant rock rich in calcium (Ca) and magnesium (Mg), is particularly promising in agriculture, due to the potential for co-delivery of multiple ecosystem services, including increased crop yield (Goll et al., 2021; Van Straaten, 2006). In fact, the positive effects on soil and crops are the primary current reason for the use of basalt and other silicates in agriculture (Haque et al., 2020a; Leonardos et al., 1987; Van Straaten, 2006; Wang, Wang, et al., 2018; Zhang et al., 2018). Another potential application that is gaining interest is the use of silicates for nature restoration, as this would help to abate soil acidification and replenish soil calcium (Likens, 2017; Peters et al., 2004; Taylor et al., 2021).

Early lab experiments and modeling indicate the highest potential for ESW on cation-depleted soils in humid and warm environments (Amann & Hartmann, 2019). Estimates of the global inorganic C sequestration potential of ESW range widely between 0.5 and 5 Gt CO_2 $year^{-1}$ (depending on cost assumptions, among others; Beerling et al., 2020; Fuss et al., 2018; Goll et al., 2021). This emphasizes the clear potential of ESW to provide a substantial part of the required decarbonization. However, the uncertainty on current estimates derived from the lab experiments and modeling is large and the largest uncertainties concern the in natura weathering rate, the co-benefit of increased plant growth, and associated C sequestration (Fuss et al., 2018; Goll et al., 2021). Field assessments of inorganic C sequestration by ESW indicate large variability, even between sites with similar climate, soil, silicate material, and rate of application (Haque et al., 2020a). Moreover, in the real world, processes such as secondary mineral formation, soil pore water saturation, and low water-silicate contact rates can substantially slow down weathering rates (Zhang et al., 2018)—as was the case in one of the first ESW mesocosm experiments (Amann et al., 2020). In addition, ESW will almost certainly impact primary production, soil organic carbon (SOC) sequestration, and soil GHG emissions. These impacts will affect the climate change mitigation potential of ESW but have not yet been considered in current calculations.

2 | BIOTA STIMULATING SILICATE WEATHERING

We postulate that biota are key to understanding the effect of ESW on atmospheric GHG concentrations and anticipate that an explicit consideration of the biotic context is necessary to unlock ESW's full climate change mitigation potential (Figure 2). Much of our ESW knowledge is derived from lab experiments that excluded biota such as plants and soil fauna, although it is known that natural weathering is strongly influenced by biota (Berner, 2004). Many biota have evolved mechanisms to enhance the weathering of minerals

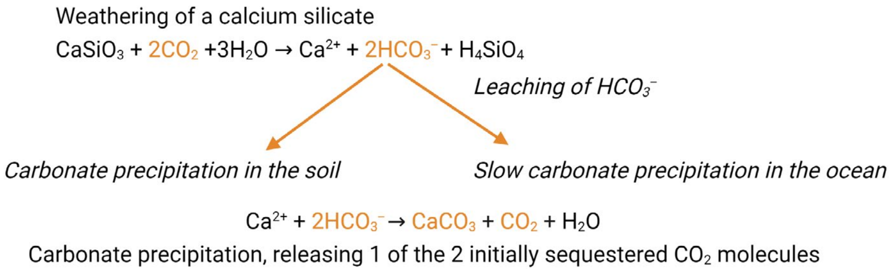
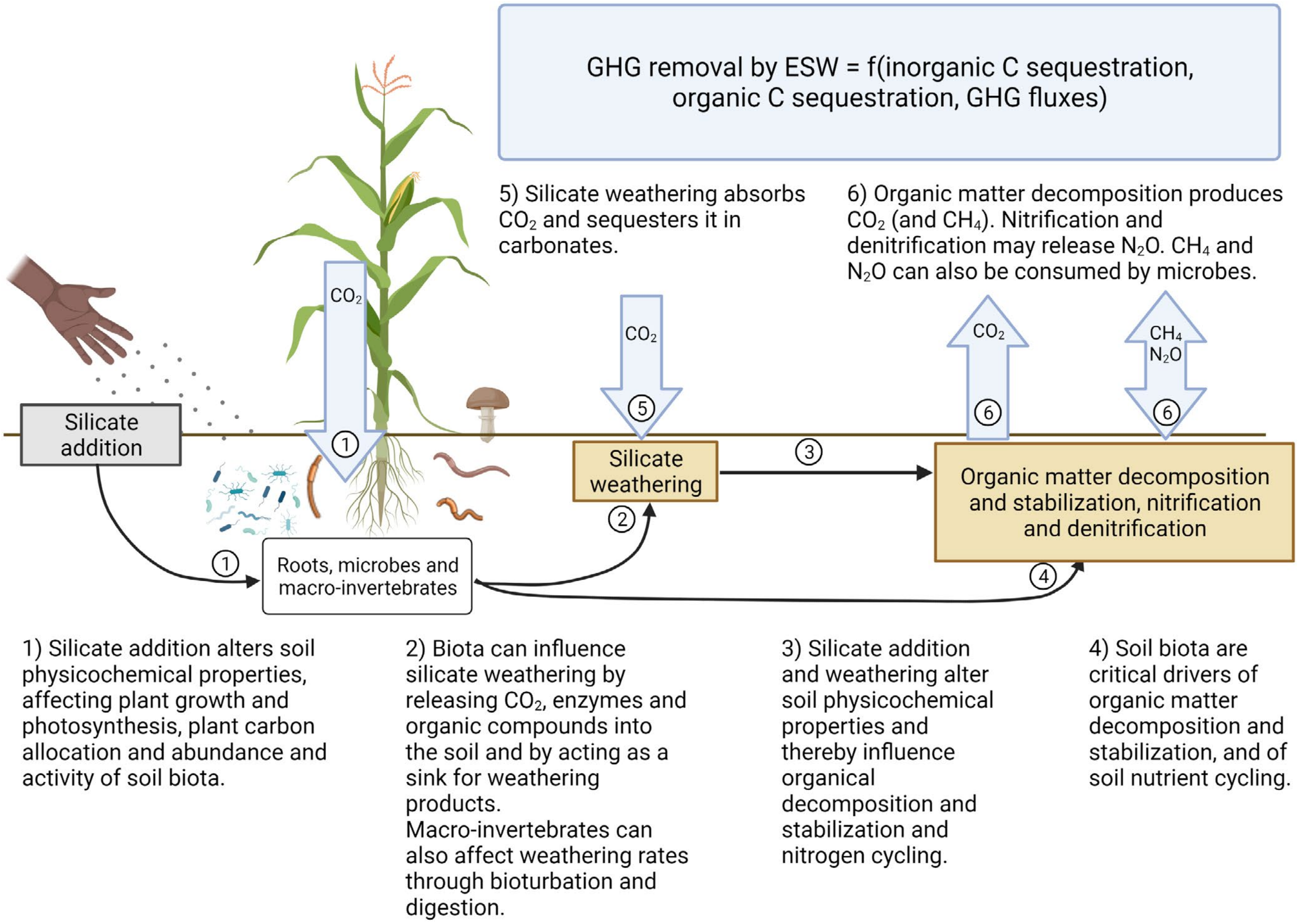


FIGURE 1 Simplified silicate weathering reaction indicating the two pathways: Bicarbonate leaching out of the system and carbonate precipitation in the soil



5) Silicate weathering absorbs CO_2 and sequesters it in carbonates.

6) Organic matter decomposition produces CO_2 (and CH_4). Nitrification and denitrification may release N_2O. CH_4 and N_2O can also be consumed by microbes.

1) Silicate addition alters soil physicochemical properties, affecting plant growth and photosynthesis, plant carbon allocation and abundance and activity of soil biota.

2) Biota can influence silicate weathering by releasing CO_2, enzymes and organic compounds into the soil and by acting as a sink for weathering products. Macro-invertebrates can also affect weathering rates through bioturbation and digestion.

3) Silicate addition and weathering alter soil physicochemical properties and thereby influence organical decomposition and stabilization and nitrogen cycling.

4) Soil biota are critical drivers of organic matter decomposition and stabilization, and of soil nutrient cycling.

FIGURE 2 Overview of the biota/silicate-weathering interactions and their influence on the greenhouse gas (GHG) removal potential of enhanced silicate weathering (ESW). Blue arrows show major GHG fluxes that can be positively or negatively influenced directly or indirectly by ESW. GHG removal through ESW includes not only inorganic C sequestration through the weathering reaction, but also covers the effect of silicate addition on soil organic C sequestration and soil GHG emissions

and access the nutrients contained in them (Dontsova et al., 2020; Zaharescu et al., 2020). During Earth's history, this biotic stimulation of mineral weathering has substantially altered the mobilization of multiple macro- and micro-elements (Bergman et al., 2004; Zaharescu et al., 2020), inducing for example global shifts in the provision of dissolved silicates to aquatic and marine ecosystems (Derry et al., 2005; Falkowski et al., 2004; Kidder & Gierlowski-Kordesch, 2005). Without such biological influences on weathering, the Earth might be considerably warmer than today due to comparably low abiotic weathering rates (Schwartzman & Volk, 1989). Despite the profound effect of biota on the weathering process, surprisingly little attention has been paid to their role in optimizing ESW efficiency, and to their role in ESW in general.

Below, we first discuss the potential effects of plants, microbes, and macro-invertebrates on ESW, which can in part be derived from the knowledge on natural (geological) weathering. In the following section, we evaluate the expected responses of biota to the implementation of ESW. Then, we discuss how ESW may interact with SOC stocks, and GHG emissions in general, and lastly, we provide a way forward in addressing the most important questions that arise.

2.1 | Plants

Plant roots can create physicochemical conditions that accelerate the dissolution of silicate minerals (Burghelea et al., 2015; Drever, 1994; Hinsinger, 1998; Hinsinger et al., 2001). They also improve soil structure and hydrology (Angers & Caron, 1998), possibly stimulating weathering rates. A recent microplot study found up to 10-fold higher inorganic C sequestration in planted compared to unplanted soils amended with silicates (Haque et al., 2020b). Roots take up elements such as Si, Mg, Ca, and Fe that are released during weathering, and thereby avoid pore water saturation with reaction products to slow down weathering rates (Harley & Gilkes, 2000; Hinsinger, 1998). Note that this plant uptake can also affect the estimation of weathering rates based on soil concentrations of these elements (and not on inorganic C pools and fluxes). By releasing protons and CO_2, roots reduce soil pH and increase the CO_2 concentration in the rhizosphere (Lenzewski et al., 2018), both of which stimulate mineral weathering (Harley & Gilkes, 2000). Plant roots also exude organic compounds such as malate or citrate that can for example protect the plant from Al intoxication (Ryan et al., 2001), while also stimulating mineral weathering by chelating reaction products and dissolving silicate minerals (Dontsova et al., 2020; Drever, 1994; Zhang & Bloom, 1999). Moreover, organic acids can dissolve silicate minerals at near-neutral pH, where abiotic dissolution rates are limited (Harley & Gilkes, 2000). The latter compounds may be particularly relevant for ESW applications in soils that are not acidic.

Plant effects on ESW are expected to differ among species, and this is likely (in part) related to nutrient acquisition strategy. Haque, Santos, et al. (2019), for example, reported that in soils treated with wollastonite, weathering rates were higher with leguminous beans than with non-leguminous corn or for bare soil without plants. Most leguminous plants such as beans and soybean live in symbiosis with nitrogen-fixing bacteria and the H^+ excreted during N_2 fixation by legumes acidifies the soil. This acidification is more pronounced for temperate than for tropical legumes (Bolan et al., 1991), which may lead to differences in their effect on ESW between climatic regions. Moreover, exudation of proteins, phenols, sugars, and free amino acids may even differ among genotypes, as has been reported for soybean (Krishnapriya & Pandey, 2016) and maize (Gaume et al., 2001). This may open possibilities for the engineering of plant-soil combinations optimized for climate change mitigation through ESW.

2.2 | Microbes

About 90% of land plant species live in symbiosis with mycorrhizal fungi (Brundrett & Tedersoo, 2018). Mycorrhizal fungi are thought to have significantly increased mineral dissolution rates at evolutionary timescales and experiments have shown that they indeed stimulate rock weathering (Bonneville et al., 2011; Burghelea et al., 2015, 2018; Zaharescu et al., 2020). Given that mycorrhizal fungi depend on their host for C, their influence on ESW is likely to be strongly related to plant activity and plant C allocation. Depending on soil conditions, plants can allocate substantial amounts of C to mycorrhizal fungi (Ven et al., 2020), and thereby stimulate their weathering activity, increasing the release of P and other mineral elements from the silicate minerals (Verbruggen et al., 2021).

Other fungi can also accelerate weathering; mineral dissolution rates can be 10 times higher underneath individual fungal filaments compared to areas where fungi are absent (Wild et al., 2021). Fungi accelerate weathering by exuding protons, organic acids, chelators, and by creating gradients through channeling elements away from mineral surfaces (Van Hees et al., 2006). As for plants, fungi and other microbes can also stimulate weathering by acting as a sink for weathering products (Oelkers et al., 2015). Fungal hyphae are very thin and can, therefore, interact with surfaces more tightly than plant roots can (Howard et al., 1991; Wild et al., 2021). Moreover, specific genetic pathways that stimulate the conversion of CO_2 into carbonates, and thus accelerate weathering, can be upregulated in response to exposure to minerals (Xiao et al., 2012). This suggests specific fungal adaptations toward the dissolution of minerals. The effect of fungi on ESW will likely depend on fungal species and on the extent to which elements contained in the applied silicates (e.g., Mg, Ca, Fe, and K) are limiting their growth.

Also, other microorganisms such as bacteria can stimulate weathering of rocks and minerals (Gouda et al., 2018). One of the key processes underlying microbially enhanced weathering is the lowering of pH by releasing acids, such as low molecular mass organic acids and dissolved CO_2. Some bacteria can lower pH to values as low as 2.3 (Ahmed & Holmström, 2014). Basak and Biswas (2009) found that *Bacillus mucilaginosus* significantly enhanced the K release of muscovite mica, which is among the most weathering-resistant silicate minerals (Palandri & Kharaka, 2004). In addition, both bacteria and fungi can produce chelates and enzymes that can enhance mineral dissolution rates up to 100 times (Buss et al., 2007; Sun et al., 2013; Xiao et al., 2015). Chelates like siderophores are usually specific to a single element, and their production depends on the type of geological material and soil fertility, again emphasizing high variation among microbial taxa and dependence on environmental context.

2.3 | Soil enzymes

The enzymes and proteins that play an important role in weathering of silicates are often excreted by microbes experiencing a nutritional deficiency. The extracellular excretions are biologically activated both by nutrient limitation and the proximity to the nutrient-carrying mineral (Xiao et al., 2015; Zaharescu et al., 2020). Some enzymes, such as carbonic anhydrases (CA) which are found within all domains of life and play a fundamental role in respiration, CO_2 transport, and photosynthesis, have a combined effect of both increasing silicate weathering and carbonate precipitation. A few studies have been able to show increased weathering of silicates and carbonates with added CA (Xiao et al., 2015; Zaihua, 2001). CA catalyzes the equilibrium reaction between CO_2 and bicarbonate ions, which in contact with the free metal ions from weathering of silicates, combine to form solid carbonate precipitates such as calcite ($CaCO_3$), magnesite ($MgCO_3$), dolomite ($CaMg(CO_3)_2$), or siderite ($FeCO_3$). The abiotic process of carbonate precipitation is slow and requires pH values higher than 8, whereas the addition of CA accelerates this reaction considerably (Bose & Satyanarayana, 2017). In fact, CA is one of the fastest enzymes, performing up to 10^6 CO_2 conversion reactions per second. CA is most efficient at high pH and may thus be especially important for ESW in alkaline soils.

Recently, there has been an increased interest in using CA in the industrial and agricultural sector for C sequestration and enhanced crop growth. Industrial slag waste from the steel industry is regularly used as a soil fertilizer due to its composition of bio-essential nutrients such as phosphates, silicates, and trace elements, which can increase crop productivity (Reddy et al., 2019; Wang, Zeng, et al., 2018). Das, Kim, et al. (2019) suggested that the use of CA-containing bacteria in slag-fertilized soils could accelerate the weathering of the silicate-containing slags and hence C sequestration.

An enhanced microbial expression of CA genes will promote the generation of H_2CO_3 and a concomitant increase of silicate weathering and a release of the bio-necessary nutrients. Some organisms adapt to increasing CO_2 levels by downregulating the gene expression of CA (Xiao et al., 2015). Experiments with fungi have shown that one way to keep an upregulated CA expression despite high CO_2 concentrations is to limit K availability and add K-feldspar as the only available source of K (Sun et al., 2013; Xiao et al., 2012). This can be seen also in environments with Ca deficiency, where silicates are the only available source for Ca (Xiao et al., 2015). High concentrations of Zn and Fe, on the contrary, stimulate CA activity, while the complex binding of Zn is a strong inhibitor of zinc metalloenzymes such as CA (Borja et al., 1998).

Urease is another enzyme used by prokaryotes and eukaryotes for efficient biomineralization. Urease is a nickel metalloenzyme that catalyzes the conversion of urea to ammonia with the side effects of raising pH, which in turn stimulates carbonate precipitation. As with CA, urease increases pH locally and is inhibited by low pH. Moghal et al. (2020) tested the retention of heavy metals in soils by inducing carbonate precipitation using urease. They found that urease efficiently precipitated carbonates which had the coupled effect of also decreasing heavy metal concentrations in the soils. Enhanced weathering of ultramafic silicate minerals such as olivine can release heavy metals such as Ni and Cr, but with the addition of urease, the toxic effect of those metals may be diminished. In other words, urease may not only increase weathering rates, but may also help in overcoming potential heavy metal contamination upon the addition of some silicate materials. This would be particularly interesting to further investigate for fast-weathering minerals such as olivine that contain high amounts of Ni and Cr.

In contrast, high urease activity can be undesirable in agriculture. Urea ammonium nitrate (UAN) is a commonly used fertilizer. When added to soil, UAN is quickly converted to ammonia and volatilized to the atmosphere (Wang, Köbke, et al., 2020), leading to fertilizer losses and increasing emissions of the potent GHG N_2O. There is, thus, a great need for more efficient use of N in fertilizers and since urease is the main enzyme responsible for the conversion of urea to NH_3, urease inhibitors have effectively been used for lowering the volatilization of urea and increasing crop yield (Drury et al., 2017; Mira et al., 2017; Wang, Köbke, et al., 2020). Humic acids are among the more efficient inhibitors of urease. Humic acids irreversibly inhibit the hydrolytic decomposition of urea (Liu et al., 2019) and concomitantly reduce urease-induced carbonate precipitation. On the contrary, the natural concentration of humic acids in soils is likely too low to have a profound impact on the precipitation capacity of urease (Al-Taweel & Abo-Tabikh, 2019; Moghal et al., 2020).

While urease can stimulate silicate weathering through carbonate biomineralization, agricultural practices aimed at reducing urease activity can limit this effect. An alternative pathway that would reconcile the interest in C sequestration and reduction of N losses is to inhibit the total conversion of urea to gas by increasing the efficiency by which plants and/or microorganisms make use of the added urea fertilizer. Interestingly, the addition of Ni—the urease co-factor present in several silicate materials—may aid in this regard. Laboratory studies have shown that supplementation of Ni to the soil increased the health and growth rate of lettuce plants (Khoshgoftarmanesh et al., 2011; Oliveira et al., 2013). Adding silicate materials containing Ni may thus stimulate biomineralization of $CaCO_3$ by urease, and hence C sequestration (Bachmeier et al., 2002), while at the same time stimulating plant growth and reducing urea volatilization. It is, however, not yet fully understood how the net fertilizer efficiency and gas-exchange rate will develop on a larger timescale (Tosi et al., 2020) and more research is needed to investigate the effects of combined urease and silicate addition on GHG emissions and plant growth.

2.4 | Macro-invertebrates

Earthworms are important ecosystem engineers (Blouin et al., 2013). It is long known that through their burrowing and feeding, earthworms strongly affect soil physicochemical as well as biological parameters. Through ingestion of fresh residue and soil particles, they can increase mineralization and mineral dissolution, leading to large local increases in nutrient availability (Van Groenigen et al., 2019). Recent research has also shown that the availability of nutrients such as P can greatly increase during earthworm gut passage due to competitive desorption reactions with dissolved organic C (Ros et al., 2017). To test the effects of earthworms on mineral dissolution, de Souza et al. (2013, 2018) added gneiss and steatite rock powder to vermicompost containing the earthworm species *Eisenia andrei*. They found that earthworms increased rock weathering and nutrient release, indicated by higher maize yields, albeit only statistically significantly for steatite (de Souza et al., 2013).

Interestingly, several common earthworm species sequester significant amounts of inorganic C by producing calcium carbonate in their specialized calciferous glands (Briones et al., 2008; Darwin, 1892; Lambkin et al., 2011; Versteegh et al., 2014). Although the purpose of these glands remains a topic of debate, they may contribute to increasing weathering rates and C sequestration. The worm digestive system can also promote mineral weathering by inoculating mineral surfaces with microbes and stimulating microbial activity, albeit dependent on the minerals that are used (Carpenter et al., 2007; Liu et al., 2011). Hu et al. (2018) isolated various silicate dissolving bacteria from the gut of earthworms and found that they increased quartz and feldspar weathering. Furthermore, inoculating potting soils with the isolated bacteria significantly increased soluble Si contents, and thereby enhanced Si uptake and growth of maize seedlings. Last, the positive effects of earthworms on soil structure and drainage (Blouin et al., 2013) can potentially help to distribute silicate grains to deeper soil layers and accelerate the infiltration of water in soils, decreasing the risk for saturation of soil pore water with reaction products.

Ants too might enhance weathering rates (Dorn, 2014). They are abundant in most terrestrial ecosystems, where they influence biogeochemical cycling and mineral weathering (Viles et al., 2021). Ants alter soils in various ways, including effects on soil pH, water infiltration, organic matter accumulation, and mineral weathering.

Several ant species produce organic acids such as formic acid, which can stimulate rock weathering (Viles et al., 2021). In a 25-year-long experiment, Dorn (2014) placed grains of plagioclase and olivine in ant nests and estimated dissolution rates that were 60 to 330 times higher than in the control plots. On the one hand, ants may thus be potentially powerful biotic weathering agents, while on the other hand, their area of influence is likely diminishing with distance from the nest. More research is still needed on the role that ants play in natural and enhanced rock weathering, to unravel the mechanisms involved, including interactions with other biota, and to quantify their potential effect on ESW.

3 | IMPACT OF ESW ON BIOTA

If biota are important in steering weathering rates, their response to silicate addition will be critical for the climate change mitigation effect of ESW. Biotic responses to silicate addition will co-determine their influence on the weathering rates (Figure 2). Moreover, side effects on biodiversity associated with changes in the trophic status of ecosystems induced by ESW could occur and both positive and negative effects on plants and soil biota may have environmental, economic, and/or health consequences. These will influence the desirability and societal acceptance of ESW and will thus co-determine the feasibility of ESW in agriculture and in more natural settings.

3.1 | Plants

Many silicates that can be used for ESW contain mineral nutrients that plants need to grow, including P, Mg, Ca, K, Fe, Zn, and Si. As a result, ESW can stimulate plant growth and increase crop yield (Battles et al., 2014; Haque, Chiang, et al., 2019; Kelland et al., 2020; Swoboda et al., 2021; Taylor et al., 2021; Van Straaten, 2006), although this is not always the case (Haque et al., 2020b; Swoboda et al., 2021; Wang, Wang, et al., 2018). Of particular importance might be the widely neglected supply of Si, which is considered a beneficial rather than an essential nutrient, although there is wide agreement and accumulating evidence that Si can induce a broad range of plant biotic and abiotic stress resistances (Epstein, 1999; Guntzer et al., 2012; Haynes, 2014). Besides improved plant growth, ESW has been suggested to increase crop resistance to pests and drought, mainly due to increased Si uptake (Guntzer et al., 2012; Van Bockhaven et al., 2013). Furthermore, 7 of the 10 most important crops are considered to be Si-accumulators (FAOSTAT, 2018; Figure 3), and yield increases in response to Si fertilization have been frequently demonstrated, for example for wheat, rice, and sugarcane (Korndörfer & Lepsch, 2001; Liang et al., 2015; Neu et al., 2017). The latter two tropical crops are typically grown on highly weathered and desilicated soils, with Si concentrations usually 5–10 times lower than that for temperate soils. The demand for Si in agriculture is therefore expected to increase in the future (Haynes, 2014).

A positive effect of silicate addition on plant growth and defense can create a positive feedback with ESW, especially if root production and belowground inputs increase. Moreover, positive growth responses can increase C sequestration in plant biomass if silicates are applied in (semi-)natural ecosystems where biomass can accumulate (Goll et al., 2021). On the contrary, it might be concerning that ESW is accompanied by the release of heavy metals like Ni and Cr (Beerling et al., 2018; Haque, Chiang, et al., 2020; Hartmann et al., 2013). Nonetheless, the application of Ni is not necessarily problematic and below a certain threshold, Ni may even be beneficial for plants (Ahmad et al., 2011; Kumar et al., 2018). In one experiment, barley growth and yield increased with Ni additions of up to 10 mg Ni kg^{-1} soil (Kumar et al., 2018). When the concentration of Ni exceeded those thresholds, growth, and yield declined, while the uptake of Ni continued to increase with increasing Ni application to soil. This suggests that Ni accumulation in the food chain is proportional to the Ni addition. The application rate and choice of silicate minerals can be adjusted to control the heavy metal release (Haque, Chiang, et al., 2020). In addition, phytoremediation may in some cases pose a way to mitigate the concentration of contaminants

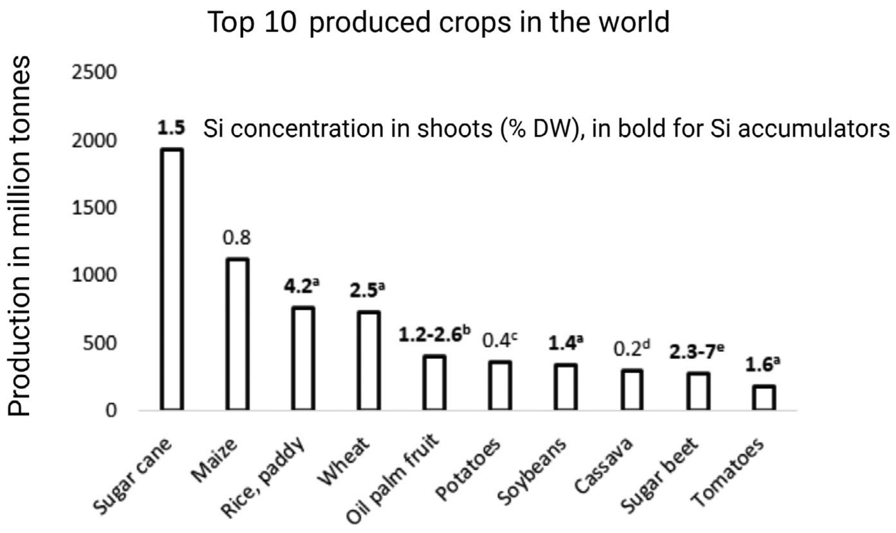


FIGURE 3 Top 10 produced crops in the world in 2018 (FAOSTAT, 2018). Seven of these crops are classified as Si accumulators (>1.0% Si of dry weight [DW]). The values above the bar are average shoot Si concentrations [a]compiled from Hodson et al. (2005); [b]averages compiled from Munevar and Romero (2015); [c]estimated averages of the data (Solanaceae) compiled by Hodson et al. (2005); [d]estimated averages of the data (Euphorbiaceae) compiled by Hodson et al. (2005); [e]averages computed from the data of Draycott (2008)

such as Ni in soil. As for urease, the potential of phytoremediation to reduce heavy metal availability following, for example, olivine application requires further investigation.

3.2 | Microbes

Large shifts in soil microbial communities have been associated with the addition of silicates (Carson et al., 2007; Das, Gwon, et al., 2019; Zhou et al., 2018). For example, Zhou et al. (2018) observed changes in bacterial and fungal community composition and reported a decrease in the abundance of microbial plant pathogens with silicate addition, likely related to improved crop defense. Soil pH is one of the main determinants of microbial community composition (Fierer, 2017), and pH changes following silicate addition will thus directly influence which microbial taxa flourish (Das, Gwon, et al., 2019; Fierer, 2017).

Silicate rock powder addition had contrasting effects on soil microbes in three Austrian forest soils with varying pH (Mersi et al., 1992). The rock powder additions increased the pH of all soils, but the most significant effects on microbial processes were found for a Calcaric Regosol and Cambisol (pH 5.8), where the rock powder additions increased nitrification, microbial biomass and respiration, xylanase, and protease activity. Intermediate effects were found for a Stagno-Mollic Gleysol (pH 3.8), where protease activity increased but phosphatase activity decreased, whereas no effects were found on a highly acidic Stagno-Dystric Gleysol (pH 2.8). An increase in xylanase, phosphatase, and protease activity—essential enzymes for the breakdown of organic matter—could increase soil CO_2 emissions. However, even though rock powder additions increased the protease content of both the Stagno-Mollic Gleysol and the Calcaric Regosol and Cambisol, CO_2 emissions and microbial biomass only increased for the Regosol and Cambisol. The rock powders also increased the nitrification and nitrate contents of the Regosol and Cambisol, which could increase N_2O emissions. Simultaneous N_2O reductions might, however, be achieved through the reduction of soil acidity, as discussed in detail below. These findings illustrate that the effect of ESW on microbial communities depends on soil properties and hence also the feedback to ESW is likely to vary depending on environmental conditions.

In general, we can expect shifts toward microbial taxa that are better able to occupy new niches on mineral surfaces or those that profit from the released nutrients (Barker et al., 1998; Gleeson et al., 2006; Reith et al., 2015). Also, the tolerance to toxic trace elements such as Ni or Cu, which can negatively impact microbes (Silva et al., 2012), can play a role. The various interactions between microbes and added silicate minerals can be expected to lead to a dynamic equilibrium between microbial community composition and mineral weathering. This may impact various soil processes relevant for soil C sequestration and GHG emissions, as illustrated by the observed increases in the abundance of functional genes involved in the degradation of labile C, fixation of C and N, and CH_4 oxidation (Das, Gwon, et al., 2019).

3.3 | Macro-invertebrates

Few experiments have tested the effect of silicate additions on macro-invertebrates and to the best of our knowledge, these experiments have yet been limited to earthworms and rock powders mixed into vermicompost and manure. Divergent responses were reported, with earthworm growth increasing in some cases and decreasing in others, depending on the rock type and amount that was applied (de Souza et al., 2019; Zhu et al., 2013).

We propose three main pathways through which applying silicate minerals might affect earthworm functioning. First, the increase in pH and basic cations upon silicate addition may positively affect earthworm communities, especially in highly weathered, low pH soils. It is well known that earthworms are absent in soils with a pH lower than 3.5, and very scarce at pH lower than 4.5. Optimal pH ranges differ per species, but are generally within the range 5.0–7.4 (Curry, 2004). In addition, increased availability of basic cations such as Ca and Mg has been shown to increase earthworm populations (Fragoso & Lavelle, 1992) and a recent study showed a clear increase in the earthworm biomass after prolonged liming of forest soil (Persson et al., 2021).

Second, there may be physical interactions between earthworms and added minerals. It has only recently been established that the thickness of the body wall of earthworms varies between species and may affect their functioning in the soil (Briones & Álvarez-Otero, 2018). Although this is so far mostly related to susceptibility to desiccation and burrowing behavior, earthworms with thicker body walls might be a better fit to function in systems where sharp mineral particles are added. This and the possibility of mechanical damage upon ingestion remain to be investigated.

Finally, as with plants and microorganisms, the release of toxic trace elements might be detrimental to earthworms. Earthworms can be affected by increased concentrations of, for example, Cu and Ni, especially under conditions of low pH when more cations are desorbed (Ma, 1988; Wang, Xia, et al., 2020), although in general they are fairly tolerant to most heavy metals (Ireland, 1983). Accordingly, de Souza et al. (2019) found that the high concentrations of Ni and Cr released during the dissolution of steatite did not hinder earthworm growth.

4 | IMPACT OF ESW ON SOC STORAGE

In order to forecast the net effect of silicate addition on the C balance of an ecosystem, the impact of ESW on the largest pool of ecosystem C, that is, SOC must be taken into account. Here too, we expect biota/silicate-weathering interactions to play a critical role. Empirical data on the effects of silicate addition are still scarce, but Anda et al. (2013) applied basalt powder to an oxisol and observed significantly increased cacao plant growth and higher SOC stocks. Moreover, mineral weathering has previously been identified as the main driver of SOC sequestration across a natural weathering chronosequence (Doetterl et al., 2018). Doetterl et al. (2018) showed that primary mineral weathering was associated with increases in nutrient availability and higher potential of soils to stabilize carbon. Hence, similar to liming and fertilization, silicate addition can be expected to impact SOC sequestration by affecting the quantity of plant belowground C inputs, as well as the stabilization of these inputs in soil organic matter (SOM; Paradelo et al., 2015; Van Sundert et al., 2020). Depending on soil heterogeneity and the magnitude of the effect, it may take several years though before such changes in SOC stocks are detectable (Paradelo et al., 2015).

Plant belowground C inputs depend on plant productivity and C allocation patterns. Plants allocate substantial amounts of C belowground in the form of roots and exudates and through symbiosis with mycorrhizal fungi (Ven et al., 2019; Verlinden et al., 2018). Nutrient availability is a key driver of plant C allocation and plant C inputs to the soil are likely to be affected by silicate addition, although the magnitude and direction of the effect is expected to depend on environmental conditions (Litton et al., 2007; Poorter et al., 2012; Ven et al., 2020; Vicca et al., 2012). Especially soil nutrient status and plant growth responses to the silicate additions are expected to be important in this regard.

Stable SOM can be formed via two major pathways: Turnover of new C inputs and modification of organic matter present in the soil. Turnover of new C depends strongly on the recalcitrance of litter and rhizodeposits. Although decomposition of recalcitrant litter is slower than that of labile litter, cumulative C losses during decomposition of recalcitrant litter are generally higher than C losses from more labile inputs (Cotrufo et al., 2013). This is because a larger fraction of the labile C can be converted into microbial biomass and microbial products. The close association between microbes and soil mineral surfaces then explains the greater stabilization of labile C inputs than of recalcitrant C inputs (Cotrufo et al., 2013). As with liming, silicate addition may increase plant C inputs and/or its nutrient concentrations (Forey et al., 2015; Melvin et al., 2013; Paradelo et al., 2015) and hence increase SOM stabilization.

Liming and silicate addition can affect SOM formation and decay via the altered activity of extracellular enzymes, driven by the modified soil pH (Sinsabaugh et al., 2008). Many C- and N-acquiring enzymes increase in potential activity after the application of lime to acid soils (Acosta-Martínez & Tabatabai, 2000). Increased pH upon silicate addition can thus accelerate the decomposition of plant litter and SOM (Leifeld et al., 2013), resulting in reduced litter and SOC stocks, but the improved living conditions are likely to result in enhanced microbial growth and thus also increase the formation of stabilized SOM.

The aggregate formation is also a key SOM stabilization mechanism that can be increased by the presence of secondary minerals formed during mineral weathering (Doetterl et al., 2018) and is influenced also by soil organisms (Lehmann et al., 2017; Thomas et al., 2020). Given that aggregates are hotspots of biological activity and biogeochemical processes (Or et al., 2021), weathering rates may be higher inside aggregates than in the surrounding soil. On the contrary, reduced water flow may lead to saturation of the water inside the aggregates, reducing weathering rates. The release of Ca from basalt can stimulate aggregation through enhanced flocculation of clay minerals, an effect possibly enhanced by earthworm activity (Shipitalo & Protz, 1989), and the formation of complexes between Ca and high-molecular-weight organic compounds (Baldock & Skjemstad, 2000; Rowley et al., 2018). Furthermore, carbonate minerals are known to improve soil structure and can act as cementing agents in the occlusion of SOM, although uncertainty exists on the importance of this mechanism for field SOC stocks (Fernández-Ugalde et al., 2014; Rowley et al., 2021).

Besides litter recalcitrance, enzyme activities, and aggregate formation, interactions between silicate minerals and SOM can impact SOC sequestration. Ca released during weathering impacts organo-mineral association via the mediation of complexation processes (Rowley et al., 2021) and during the weathering of some silicates such as basalt, substantial amounts of Fe- and Al-oxi-hydroxides are formed. The latter has a strong SOM stabilization potential and the presence of such reactive minerals can increase SOC sequestration (Abramoff et al., 2021; Cotrufo et al., 2013; Or et al., 2021).

Finally, changes in SOM decomposition, for example, due to altered litter quality or aggregate formation, may also impact weathering rates, creating a feedback loop. For example, faster turnover of higher quality litter can increase the soil CO_2 concentration, impacting mineral dissolution. At the same time, increased litter turnover enhances the dissolution of organic matter (Cotrufo et al., 2013), and thus increases the potential of organic compounds to either form stable organo-mineral complexes or aid in the weathering. Overall, the balance between the effects on plant C inputs, litter decomposition, and SOM stabilization will determine the net effect of silicate addition on SOC sequestration. In the case of liming, a literature review by Paradelo et al. (2015) showed that SOC stocks generally increased with liming in mineral soils. In organic soils and (acid) organic soil horizons, increased mineralization rates upon liming appear more likely to reduce SOC stocks (Lundström et al., 2003; Paradelo et al., 2015).

In determining the net effect of ESW on soil C budgets, it is important to consider both inorganic and organic C sequestration and the interactions among the different processes involved. In doing so, the various timescales at which sequestration mechanisms are active need to be considered. Mean residence times of soil organic and inorganic C differ by orders of magnitude, and the persistence of SOC varies widely depending on the location and form of SOC (Schmidt et al., 2011; Zamanian et al., 2016). Moreover, biological responses to silicate weathering might reach saturation on shorter timescales, depending on silicate applications and environmental conditions (Goll et al., 2021). This calls for a better understanding of the extent to which amplifying and dampening biotic responses saturate, as well as the respective timescales. A combination of targeted field experiments and theoretical modeling is required to span the large range of timescales from responses of microbes to SOM stabilization. Soil development chronosequences could provide information on the long-term impact of ESW (Doetterl et al., 2018) as ESW-focused studies are still scarce and (yet) of short duration.

5 | ESW EFFECTS ON OTHER GHG EMISSIONS

Silicate addition has been suggested to affect soil emissions of GHGs other than CO_2, especially N_2O (Figure 1; Beerling et al., 2018). Total annual N_2O emissions from soils in natural and agricultural systems together represent about 55% of all global N_2O sources (Tian et al., 2020). Agricultural soils are a major source of N_2O to the atmosphere due to the high amount of mineral fertilizers that increase microbial N availability (Guenet et al., 2021). Soil moisture is a key determinant of soil N_2O emissions (Firestone & Davidson, 1989) and changes in soil hydrology following silicate addition can thus influence N_2O emissions (among others depending on soil texture and size of the silicate grains). Also soil pH influences N_2O emissions; low pH decreases the activity of N_2O reductase, stimulating the release of N_2O as an intermediate product of the denitrification process (Hu et al., 2015; Liu et al., 2010). Silicate addition to acid soils is expected to buffer pH and thus reduce N_2O emissions by increasing the N_2:N_2O ratio (i.e., enhancing complete denitrification; Blanc-Betes et al., 2021), similar to what has been reported for liming (Hénault et al., 2019). In aerobic soils, however, reduced N_2O release from denitrification may be counterbalanced by increased N_2O release during nitrification, as pH increases stimulate nitrification and favor ammonia-oxidizing bacteria over ammonia-oxidizing archaea, with the former producing more N_2O (Nadeem et al., 2020).

Other interactions with biota arise here as well. For example, mycorrhizal fungi have been shown to reduce N_2O emissions (Storer et al., 2018), potentially enhancing this anticipated co-benefit of ESW, whereas earthworms have been reported to increase N_2O emissions (Augustenborg et al., 2012; Lubbers et al., 2013). In some soils, earthworm activity may account for more than 50% of the total soil N_2O emissions (Augustenborg et al., 2012) due to the increase in substrate availability resulting from their activity, the anaerobic environment in their casts as well as their effect on macropore formation (Lubbers et al., 2013; Nebert et al., 2011). The interactive effect of soil biota and silicate-weathering on N_2O emissions is yet unexplored but could provide ways to increase the climate change mitigation effect of ESW. For example, growing N-fixing plants, especially temperate legumes, typically acidifies the soil (Bolan et al., 1991), possibly leading to high N_2O emissions. This effect could be countered by an increase in pH upon silicate addition. Furthermore, potential improvements of soil structure through the combination of silicate addition and biotic activity may increase soil aeration and thus reduce denitrification.

Whereas N_2O can be of huge importance in agricultural soils, methane (CH_4) typically is not. CH_4 production is a strictly anaerobic process. In aerobic soils, CH_4 oxidation typically exceeds CH_4 production, making these soils modest CH_4 sinks (Dutaur & Verchot, 2007). Rice fields, however, are an important source of CH_4 emissions due to their waterlogged anaerobic soils (Saunois et al., 2020). Some studies have reported a decrease in CH_4 emissions when adding silicates (Ali et al., 2008; Wang, Zeng, et al., 2018), while others reported an increase (Ku et al., 2020). Silicate addition can reduce CH_4 emissions by reducing methanogenesis and/or increasing CH_4 oxidation (Das, Kim, et al., 2019). Silicates containing Fe can stimulate Fe-reducing bacteria at the expense of methanogens, as Fe is a more favorable electron acceptor than CO_2 (Das, Kim, et al., 2019; Gwon et al., 2018). On the contrary, increased plant productivity in response to silicate addition may increase CH_4 emissions by increasing plant belowground C input quantity and quality (Ku et al., 2020), and enlarged aerenchyma due to higher root biomass might further increase CH_4 funneling to the atmosphere (Kim et al., 2018; Ku et al., 2020). Hence, the net effect of silicate addition on CH_4 emissions will depend on the balance between these counteracting processes.

As illustrated above, silicate addition can have diverging effects on the release of CO_2, CH_4, and N_2O, from soils and ecosystems. Reductions in the emission of one of these GHGs might be counteracted by increases in another. Ku et al. (2020), for example, reported a reduction in N_2O emissions from a rice field amended with a calcium silicate, but CO_2 and CH_4 emissions increased more, leading to an increase in the global warming potential of the cumulative GHG emissions. This illustrates the importance of considering the emissions of all three of these GHGs when assessing the climate change mitigation potential of ESW and its interaction with the biota.

6 | ADVANCES IN MODELING ESW

Few modeling studies have yet addressed interactions between ESW and biota. Most studies are limited to the dissolution reactions, removal of weathering products, abiotic CO_2 drawdown (e.g., Rinder & von Hagke, 2021; Strefler et al., 2018), and impact on soil hydrology (de Oliveira Garcia et al., 2020). Nonetheless, first models are emerging which include interactions between biota and weathering rates. Goll et al. (2021) used a comprehensive land surface model coupled to a model of mineral dissolution to simulate the effect of nutrient release from basalt on plant growth and ecosystem carbon storage. Cipolla et al. (2021) coupled an ESW component to an ecohydrological-biogeochemical soil model to investigate the combined contributions of hydrology and plants to weathering rates. Beerling et al. (2020) used a one-dimensional vertical reactive transport model with the steady-state flow, and a source term representing rock grain dissolution which includes an empirical formulation for the combined effect of biotic processes that accelerate the physical breakdown and chemical dissolution of minerals.

Land surface models which resolve the water, energy, and biogeochemical cycles in plant and soils coupled to weathering models can provide the means to study the full effect of ESW on biota and vice versa. The increasing realism of belowground processes in such models provides the basis to integrate the emerging data from experiments in biologically active soils, mesocosm, and field experiments (e.g., Kelland et al., 2020).

7 | FUTURE OUTLOOK AND RESEARCH NEEDS

We illustrated that the weathering rates and the GHG removal potential of ESW depend not only on abiotic conditions, but is potentially strongly influenced by biota, which have been largely overlooked in ESW research. The multiple soil biota/silicate-weathering interactions imply that the ultimate GHG removal effect of ESW will depend on the balance between positive and negative influences of silicates on biota, and their subsequent joint effects on inorganic and organic C and N fluxes. Further unraveling and quantifying the impact of biota on ESW will be critical for planning the widespread use of ESW as a climate change mitigation strategy. If biological processes are indeed critical in determining GHG removal by ESW, this may imply that the biota-silicate interaction determines the location of ESW hotspots, possibly overriding current assumptions regarding (climate-driven) ESW hotspots in the tropics.

Taking into account biological processes will also be critical to anticipate synergistic effects between ESW and environmental or climatic changes. For example, elevated CO_2 concentrations often increase plant growth and belowground C inputs (Terrer et al., 2021), which could in turn stimulate ESW and SOC sequestration. In addition, the nutrient limitation on the CO_2 fertilization effect may be (partly) alleviated by ESW treatments (Goll et al., 2021; Terrer et al., 2019). Warming can be expected to increase weathering rates, but may also decrease SOC sequestration as a result of increased microbial activity and decomposition (Davidson & Janssens, 2006). Moreover, as droughts increase in frequency and intensity, silicate application may reduce some of its impacts. Si accumulation in plants can reduce plant water losses (Guntzer et al., 2012) and K release through weathering may improve plant water use efficiency (Battie-Laclau et al., 2016). In-depth research is needed to quantify the effects of ESW on plants, soil, and GHG removal and this should consider interactions with nutrient cycling (Vicca et al., 2018) and other important environmental moderators subjected to global change.

Further interest in exploring the biota/silicate weathering interaction lies in the potential benefits for agriculture and nature restoration. The potential of ESW as a NET and feasibility of widespread application is not only determined by its GHG removal or GHG emission reduction potential, but also by its potential for increasing crop yield and biomass production, while at the same time avoiding environmental and health risks. Silicate rock powders and other silicate or alkaline materials (e.g., concrete fines and steel slags) are already being used to “rejuvenate” soils and to provide slow-release bioavailable nutrients. Currently, however, the positive properties of the slow-leaching rock powder nutrients are also the limitations of the material because their low solubility may render the material cost-inefficient as a fertilizing agent (Amann & Hartmann, 2019). By increasing the weathering rate with the help from biota, the drawdown of CO_2 and the soil fertilizing effects could improve, increasing the potential profit to be made with ESW application. Concerns about the release of toxic trace elements also put a constraint on the application of ESW. Here, the possibility for phytoremediation and immobilization of heavy metals contained in some fast-weathering silicate minerals such as olivine could be explored to moderate these risks. We conclude that in order to determine the true potential of ESW as a NET, as well as to maximize its climate change mitigation effect, the biotic context must be comprehensively evaluated in lab and in field settings.

ACKNOWLEDGMENTS

This research was supported by the Research Foundation—Flanders (FWO), the European Commissions (H2020 FET-open project Super Bio-Accelerated Mineral weathering: A new climate risk hedging reactor technology—“BAM”) and by the Research Council of the University of Antwerp. DSG benefited from support from the Agence Nationale de la recherche (ANR) grant ANR-16-CONV-0003 (CLAND). JP and JS research was supported by the Fundación Ramón Areces project ELEMENTAL-CLIMATE, the Spanish Government project CGL2016-79835-P, and the Catalan Government project SGR 2017-1005.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

ORCID

Sara Vicca https://orcid.org/0000-0001-9812-5837
Daniel S. Goll https://orcid.org/0000-0001-9246-9671
Mathilde Hagens https://orcid.org/0000-0003-3980-1043
Jens Hartmann https://orcid.org/0000-0003-1878-9321
Ivan A. Janssens https://orcid.org/0000-0002-5705-1787
Anna Neubeck https://orcid.org/0000-0002-1291-5529
Josep Peñuelas https://orcid.org/0000-0002-7215-0150
Sílvia Poblador https://orcid.org/0000-0002-4975-9777
Jet Rijnders https://orcid.org/0000-0001-7896-0659
Jordi Sardans https://orcid.org/0000-0003-2478-0219
Eric Struyf https://orcid.org/0000-0001-6833-4136
Jan Willem van Groenigen https://orcid.org/0000-0001-9637-0601
Arthur Vienne https://orcid.org/0000-0002-0690-2481
Erik Verbruggen https://orcid.org/0000-0001-7015-1515

REFERENCES

Abramoff, R. Z., Georgiou, K., Guenet, B., Torn, M. S., Huang, Y., Zhang, H., Feng, W., Jagadamma, S., Kaiser, K., Kothawala, D., Mayes, M. A., & Ciais, P. (2021). How much carbon can be added to soil by sorption? *Biogeochemistry*, *152*(2), 127–142. https://doi.org/10.1007/s10533-021-00759-x

Acosta-Martínez, V., & Tabatabai, M. A. (2000). Enzyme activities in a limed agricultural soil. *Biology and Fertility of Soils*, *31*(1), 85–91. https://doi.org/10.1007/s003740050628

Ahmad, M. S. A., Ashraf, M., & Hussain, M. (2011). Phytotoxic effects of nickel on yield and concentration of macro- and micro-nutrients in sunflower (*Helianthus annuus* L.) achenes. *Journal of Hazardous Materials*, *185*(2), 1295–1303. https://doi.org/10.1016/j.jhazmat.2010.10.045

Ahmed, E., & Holmström, S. J. M. (2014). Siderophores in environmental research: Roles and applications. *Microbial Biotechnology*, *7*(3), 196–208. https://doi.org/10.1111/1751-7915.12117

Ali, M. A., Lee, C. H., & Kim, P. J. (2008). Effect of silicate fertilizer on reducing methane emission during rice cultivation. *Biology and Fertility of Soils*, *44*(4), 597–604. https://doi.org/10.1007/s00374-007-0243-5

Al-Taweel, L., & Abo-Tabikh, M. (2019). Urea and ammonium sulfate fertilizers and humic acid effect on urease enzyme activity in and out the rhizosphere of *Zea mays* L. crop. *Plant Archives*, *19*(1), 1905–1914.

Amann, T., & Hartmann, J. (2019). Ideas and perspectives: Synergies from co-deployment of negative emission technologies. *Biogeosciences*, *16*(15), 2949–2960. https://doi.org/10.5194/bg-16-2949-2019

Amann, T., Hartmann, J., Struyf, E., de Oliveira Garcia, W., Fischer, E. K., Janssens, I., Meire, P., & Schoelynck, J. (2020). Enhanced weathering and related element fluxes—A cropland mesocosm approach. *Biogeosciences*, *17*(1), 103–119. https://doi.org/10.5194/bg-17-103-2020

Anda, M., Shamshuddin, J., & Fauziah, C. I. (2013). Increasing negative charge and nutrient contents of a highly weathered soil using basalt and rice husk to promote cocoa growth under field conditions. *Soil and Tillage Research*, *132*, 1–11. https://doi.org/10.1016/j.still.2013.04.005

Angers, D. A., & Caron, J. (1998). Plant-induced changes in soil structure: Processes and feedbacks. *Biogeochemistry*, *42*(1), 55–72. https://doi.org/10.1023/A:1005944025343

Augustenborg, C. A., Hepp, S., Kammann, C., Hagan, D., Schmidt, O., & Müller, C. (2012). Biochar and earthworm effects on soil nitrous oxide and carbon dioxide emissions. *Journal of Environmental Quality*, *41*(4), 1203–1209. https://doi.org/10.2134/jeq2011.0119

Bachmeier, K. L., Williams, A. E., Warmington, J. R., & Bang, S. S. (2002). Urease activity in microbiologically-induced calcite precipitation. *Journal of Biotechnology*, *93*(2), 171–181. https://doi.org/10.1016/S0168-1656(01)00393-5

Baldock, J. A., & Skjemstad, J. O. (2000). Role of the soil matrix and minerals in protecting natural organic materials against biological attack. *Organic Geochemistry*, *31*(7), 697–710. https://doi.org/10.1016/S0146-6380(00)00049-8

Barker, W. W., Welch, S. A., Chu, S., & Banfield, J. F. (1998). Experimental observations of the effects of bacteria on aluminosilicate weathering. *American Mineralogist*, *83*(11–12 Pt. 2), 1551–1563. https://doi.org/10.2138/am-1998-11-1243

Basak, B. B., & Biswas, D. R. (2009). Influence of potassium solubilizing microorganism (*Bacillus mucilaginosus*) and waste mica on potassium uptake dynamics by sudan grass (Sorghum vulgare Pers.) grown under two Alfisols. *Plant and Soil*, *317*(1), 235–255. https://doi.org/10.1007/s11104-008-9805-z

Battie-Laclau, P., Delgado-Rojas, J. S., Christina, M., Nouvellon, Y., Bouillet, J.-P., Piccolo, M. D. C., Moreira, M. Z., Gonçalves, J. L. D. M., Roupsard, O., & Laclau, J.-P. (2016). Potassium fertilization increases water-use efficiency for stem biomass production without affecting intrinsic water-use efficiency in *Eucalyptus grandis* plantations. *Forest Ecology and Management*, *364*, 77–89. https://doi.org/10.1016/j.foreco.2016.01.004

Battles, J. J., Fahey, T. J., Driscoll Jr., C. T., Blum, J. D., & Johnson, C. E. (2014). Restoring soil calcium reverses forest decline. *Environmental Science & Technology Letters*, *1*(1), 15–19. https://doi.org/10.1021/ez400033d

Beerling, D. J., Kantzas, E. P., Lomas, M. R., Wade, P., Eufrasio, R. M., Renforth, P., Sarkar, B., Andrews, M. G., James, R. H., Pearce, C. R., Mercure, J.-F., Pollitt, H., Holden, P. B., Edwards, N. R., Khanna, M., Koh, L., Quegan, S., Pidgeon, N. F., Janssens, I. A., … Banwart, S. A. (2020). Potential for large-scale CO_2 removal via enhanced rock weathering with croplands. *Nature*, *583*(7815), 242–248. https://doi.org/10.1038/s41586-020-2448-9

Beerling, D. J., Leake, J. R., Long, S. P., Scholes, J. D., Ton, J., Nelson, P. N., Bird, M., Kantzas, E., Taylor, L. L., Sarkar, B., Kelland, M., DeLucia, E., Kantola, I., Müller, C., Rau, G., & Hansen, J. (2018). Farming with crops and rocks to address global climate, food and soil security. *Nature Plants*, *4*(3), 138–147. https://doi.org/10.1038/s41477-018-0108-y

Bergman, N. M., Lenton, T. M., & Watson, A. J. (2004). COPSE: A new model of biogeochemical cycling over Phanerozoic time. *American Journal of Science*, *304*(5), 397–437. https://doi.org/10.2475/ajs.304.5.397

Berner, R. (2004). *The phanerozoic carbon cycle: CO_2 and O_2*. Oxford University Press.

Blanc-Betes, E., Kantola, I. B., Gomez-Casanovas, N., Hartman, M. D., Parton, W. J., Lewis, A. L., Beerling, D. J., & DeLucia, E. H. (2021). In silico assessment of the potential of basalt amendments to reduce N_2O emissions from bioenergy crops. *GCB Bioenergy*, *13*(1), 224–241. https://doi.org/10.1111/gcbb.12757

Blouin, M., Hodson, M. E., Delgado, E. A., Baker, G., Brussaard, L., Butt, K. R., Dai, J., Dendooven, L., Peres, G., Tondoh, J. E., Cluzeau, D., & Brun, J.-J. (2013). A review of earthworm impact on soil function and ecosystem services. *European Journal of Soil Science*, *64*(2), 161–182. https://doi.org/10.1111/ejss.12025

Bolan, N. S., Hedley, M. J., & White, R. E. (1991). Processes of soil acidification during nitrogen cycling with emphasis on legume based pastures. *Plant and Soil*, *134*(1), 53–63. https://doi.org/10.1007/BF00010717

Bonneville, S., Morgan, D. J., Schmalenberger, A., Bray, A., Brown, A., Banwart, S. A., & Benning, L. G. (2011). Tree-mycorrhiza symbiosis accelerate mineral weathering: Evidences from nanometer-scale elemental fluxes at the hypha–mineral interface. *Geochimica et Cosmochimica Acta*, *75*(22), 6988–7005. https://doi.org/10.1016/j.gca.2011.08.041

Borja, P., Alzuet, G., Casanova, J., Server-Carrio, J., Borrás, J., Martínez-Ripoll, M., & Supuran, C. (1998). Zinc complexes of carbonic anhydrase inhibitors. Crystal structure of [Zn (5-amino-1, 3, 4-thiadiazole-2-sulfonamidate) 2 (NH_3)]. H_2O. Carbonic anhydrase inhibitory activity. *Main Group Metal Chemistry*, *21*(5), 279–292.

Bose, H., & Satyanarayana, T. (2017). Microbial carbonic anhydrases in biomimetic carbon sequestration for mitigating global warming: Prospects and perspectives. *Frontiers in Microbiology*, *8*(1615). https://doi.org/10.3389/fmicb.2017.01615

Briones, M. J. I., & Álvarez-Otero, R. (2018). Body wall thickness as a potential functional trait for assigning earthworm species to ecological categories. *Pedobiologia*, *67*, 26–34. https://doi.org/10.1016/j.pedobi.2018.02.001

Briones, M. J. I., Ostle, N. J., & Piearce, T. G. (2008). Stable isotopes reveal that the calciferous gland of earthworms is a CO_2-fixing organ. *Soil Biology and Biochemistry*, *40*(2), 554–557. https://doi.org/10.1016/j.soilbio.2007.09.012

Brundrett, M. C., & Tedersoo, L. (2018). Evolutionary history of mycorrhizal symbioses and global host plant diversity. *New Phytologist*, *220*(4), 1108–1115. https://doi.org/10.1111/nph.14976

Burghelea, C. I., Dontsova, K., Zaharescu, D. G., Maier, R. M., Huxman, T., Amistadi, M. K., Hunt, E., & Chorover, J. (2018). Trace element mobilization during incipient bioweathering of four rock types. *Geochimica et Cosmochimica Acta*, *234*, 98–114. https://doi.org/10.1016/j.gca.2018.05.011

Burghelea, C., Zaharescu, D. G., Dontsova, K., Maier, R., Huxman, T., & Chorover, J. (2015). Mineral nutrient mobilization by plants from rock: Influence of rock type and arbuscular mycorrhiza. *Biogeochemistry*, *124*(1), 187–203. https://doi.org/10.1007/s10533-015-0092-5

Buss, H. L., Lüttge, A., & Brantley, S. L. (2007). Etch pit formation on iron silicate surfaces during siderophore-promoted dissolution. *Chemical Geology*, *240*(3), 326–342. https://doi.org/10.1016/j.chemgeo.2007.03.003

Carpenter, D., Hodson, M. E., Eggleton, P., & Kirk, C. (2007). Earthworm induced mineral weathering: Preliminary results. *European Journal of Soil Biology*, *43*, S176–S183. https://doi.org/10.1016/j.ejsobi.2007.08.053

Carson, J. K., Rooney, D., Gleeson, D. B., & Clipson, N. (2007). Altering the mineral composition of soil causes a shift in microbial community structure. *Fems Microbiology Ecology*, *61*(3), 414–423. https://doi.org/10.1111/j.1574-6941.2007.00361.x

Cipolla, G., Calabrese, S., Noto, L. V., & Porporato, A. (2021). The role of hydrology on enhanced weathering for carbon sequestration I. Modeling rock-dissolution reactions coupled to plant, soil moisture, and carbon dynamics. *Advances in Water Resources*, *154*, 103934. https://doi.org/10.1016/j.advwatres.2021.103934

Cotrufo, M. F., Wallenstein, M. D., Boot, C. M., Denef, K., & Paul, E. (2013). The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: Do labile plant inputs form stable soil organic matter? *Global Change Biology*, *19*(4), 988–995. https://doi.org/10.1111/gcb.12113

Curry, J. P. (2004). Factors affecting the abundance of earthworms in soils. *Earthworm Ecology*, *9*, 113.

Darwin, C. (1892). *The formation of vegetable mould through the action of worms: With observations on their habits* (Vol. 37). J. Murray.

Das, S., Gwon, H. S., Khan, M. I., Van Nostrand, J. D., Alam, M. A., & Kim, P. J. (2019). Taxonomic and functional responses of soil microbial communities to slag-based fertilizer amendment in rice cropping systems. *Environment International*, *127*, 531–539. https://doi.org/10.1016/j.envint.2019.04.012

Das, S., Kim, G. W., Hwang, H. Y., Verma, P. P., & Kim, P. J. (2019). Cropping with slag to address soil, environment, and food security. *Frontiers in Microbiology*, *10*(1320). https://doi.org/10.3389/fmicb.2019.01320

Davidson, E. A., & Janssens, I. A. (2006). Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature*, *440*(9), 165–173. https://doi.org/10.1038/nature04514

de Oliveira Garcia, W., Amann, T., Hartmann, J., Karstens, K., Popp, A., Boysen, L. R., Smith, P., & Goll, D. (2020). Impacts of enhanced weathering on biomass production for negative emission technologies and soil hydrology. *Biogeosciences*, *17*(7), 2107–2133. https://doi.org/10.5194/bg-17-2107-2020

de Souza, M. E. P., Cardoso, I. M., de Carvalho, A. M. X., Lopes, A. P., & Jucksch, I. (2019). Gneiss and steatite vermicomposted with organic residues: Release of nutrients and heavy metals. *International Journal of Recycling of Organic Waste in Agriculture*, *8*(3), 233–240. https://doi.org/10.1007/s40093-019-0244-z

de Souza, M. E. P., Cardoso, I. M., De Carvalho, A. M. X., Lopes, A. P., Jucksch, I., & Janssen, A. (2018). Rock powder can improve vermicompost chemical properties and plant nutrition: An on-farm experiment. *Communications in Soil Science and Plant Analysis*, *49*(1), 1–12. https://doi.org/10.1080/00103624.2017.1418372

de Souza, M. E. P., de Carvalho, A. M. X., de Cássia Deliberali, D., Jucksch, I., Brown, G. G., Mendonça, E. S., & Cardoso, I. M. (2013). Vermicomposting with rock powder increases plant growth. *Applied Soil Ecology*, *69*, 56–60. https://doi.org/10.1016/j.apsoil.2013.01.016

Derry, L. A., Kurtz, A. C., Ziegler, K., & Chadwick, O. A. (2005). Biological control of terrestrial silica cycling and export fluxes to watersheds. *Nature*, *433*(7027), 728–731. https://doi.org/10.1038/nature03299

Doetterl, S., Berhe, A. A., Arnold, C., Bodé, S., Fiener, P., Finke, P., Fuchslueger, L., Griepentrog, M., Harden, J. W., Nadeu, E., Schnecker, J., Six, J., Trumbore, S., Van Oost, K., Vogel, C., & Boeckx, P. (2018). Links among warming, carbon and microbial dynamics mediated by soil mineral weathering. *Nature Geoscience*, *11*(8), 589–593. https://doi.org/10.1038/s41561-018-0168-7

Dontsova, K., Balogh-Brunstad, Z., & Chorover, J. (2020). Plants as drivers of rock weathering. In K. Dontsova, Z. Balogh-Brunstad, & G. L. Roux (Eds.), *Biogeochemical cycles* (pp. 33–58). John Wiley & Sons, Inc.

Dorn, R. I. (2014). Ants as a powerful biotic agent of olivine and plagioclase dissolution. *Geology*, *42*(9), 771–774. https://doi.org/10.1130/g35825.1

Draycott, A. P. (2008). *Sugar beet*. Wiley-Blackwell.

Drever, J. I. (1994). The effect of land plants on weathering rates of silicate minerals. *Geochimica et Cosmochimica Acta*, *58*(10), 2325–2332. https://doi.org/10.1016/0016-7037(94)90013-2

Drury, C. F., Yang, X., Reynolds, W. D., Calder, W., Oloya, T. O., & Woodley, A. L. (2017). Combining urease and nitrification inhibitors with incorporation reduces ammonia and nitrous oxide emissions and increases corn yields. *Journal of Environmental Quality*, *46*(5), 939–949. https://doi.org/10.2134/jeq2017.03.0106

Dutaur, L., & Verchot, L. V. (2007). A global inventory of the soil CH_4 sink. *Global Biogeochemical Cycles*, *21*(4). https://doi.org/10.1029/2006GB002734

Epstein, E. (1999). Silicon. *Annual Review of Plant Physiology and Plant Molecular Biology*, *50*(1), 641–664. https://doi.org/10.1146/annurev.arplant.50.1.641

Falkowski, P. G., Katz, M. E., Knoll, A. H., Quigg, A., Raven, J. A., Schofield, O., & Taylor, F. J. R. (2004). The evolution of modern eukaryotic phytoplankton. *Science*, *305*(5682), 354–360. https://doi.org/10.1126/science.1095964

FAOSTAT. (2018). *Top production quantity—World (total) in 2018*. Food and Agriculture Organization of the United Nations. FAOSTAT statistical database. FAO.

Fernández-Ugalde, O., Virto, I., Barré, P., Apesteguía, M., Enrique, A., Imaz, M. J., & Bescansa, P. (2014). Mechanisms of macroaggregate stabilisation by carbonates: Implications for organic matter protection in semi-arid calcareous soils. *Soil Research*, *52*(2), 180–192. https://doi.org/10.1071/SR13234

Fierer, N. (2017). Embracing the unknown: Disentangling the complexities of the soil microbiome. *Nature Reviews Microbiology*, *15*(10), 579–590. https://doi.org/10.1038/nrmicro.2017.87

Firestone, M. K., & Davidson, E. A. (1989). Microbiological basis of NO and N_2O production and consumption in soil. *Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere*, *47*, 7–21.

Forey, E., Trap, J., & Aubert, M. (2015). Liming impacts Fagus sylvatica leaf traits and litter decomposition 25 years after amendment. *Forest Ecology and Management*, *353*, 67–76. https://doi.org/10.1016/j.foreco.2015.03.050

Fragoso, C., & Lavelle, P. (1992). Earthworm communities of tropical rain forests. *Soil Biology and Biochemistry*, *24*(12), 1397–1408. https://doi.org/10.1016/0038-0717(92)90124-G

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente, J. L. V., Wilcox, J., del Mar Zamora Dominguez, M., & Minx, J. C. (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters*, *13*(6), 063002. https://doi.org/10.1088/1748-9326/aabf9f

Gasser, T., Guivarch, C., Tachiiri, K., Jones, C. D., & Ciais, P. (2015). Negative emissions physically needed to keep global warming below 2°C. *Nature Communications*, *6*(1), 7958. https://doi.org/10.1038/ncomms8958

Gaume, A., Mächler, F., De León, C., Narro, L., & Frossard, E. (2001). Low-P tolerance by maize (*Zea mays* L.) genotypes: Significance of root growth, and organic acids and acid phosphatase root exudation. *Plant and Soil*, *228*(2), 253–264.

Gleeson, D. B., Kennedy, N. M., Clipson, N., Melville, K., Gadd, G. M., & McDermott, F. P. (2006). Characterization of bacterial community structure on a weathered pegmatitic granite. *Microbial Ecology*, *51*(4), 526–534. https://doi.org/10.1007/s00248-006-9052-x

Goll, D. S., Ciais, P., Amann, T., Buermann, W., Chang, J., Eker, S., Hartmann, J., Janssens, I., Li, W., Obersteiner, M., Penuelas, J., Tanaka, K., & Vicca, S. (2021). Potential CO_2 removal from enhanced weathering by ecosystem responses to powdered rock. *Nature Geoscience*. https://doi.org/10.1038/s41561-021-00798-x

Goll, D. S., Moosdorf, N., Hartmann, J., & Brovkin, V. (2014). Climate-driven changes in chemical weathering and associated phosphorus release since 1850: Implications for the land carbon balance. *Geophysical Research Letters*, *41*(10), 3553–3558. https://doi.org/10.1002/2014GL059471

Gouda, S., Kerry, R. G., Das, G., Paramithiotis, S., Shin, H.-S., & Patra, J. K. (2018). Revitalization of plant growth promoting rhizobacteria for sustainable development in agriculture. *Microbiological Research*, *206*, 131–140. https://doi.org/10.1016/j.micres.2017.08.016

Guenet, B., Gabrielle, B., Chenu, C., Arrouays, D., Balesdent, J., Bernoux, M., Bruni, E., Caliman, J.-P., Cardinael, R., Chen, S., Ciais, P., Desbois, D., Fouche, J., Frank, S., Henault, C., Lugato, E., Naipal, V., Nesme, T., Obersteiner, M., … Zhou, F. (2021). Can N_2O emissions offset the benefits from soil organic carbon storage? *Global Change Biology*, *27*(2), 237–256. https://doi.org/10.1111/gcb.15342

Guntzer, F., Keller, C., & Meunier, J.-D. (2012). Benefits of plant silicon for crops: A review. *Agronomy for Sustainable Development*, *32*(1), 201–213. https://doi.org/10.1007/s13593-011-0039-8

Gwon, H. S., Khan, M. I., Alam, M. A., Das, S., & Kim, P. J. (2018). Environmental risk assessment of steel-making slags and the potential use of LD slag in mitigating methane emissions and the grain arsenic level in rice (*Oryza sativa* L.). *Journal of Hazardous Materials*, *353*, 236–243. https://doi.org/10.1016/j.jhazmat.2018.04.023

Haque, F., Chiang, Y. W., & Santos, R. M. (2019). Alkaline mineral soil amendment: A climate change 'StabilizationWedge'? *Energies*, *12*, 2299. https://doi.org/10.3390/en12122299

Haque, F., Chiang, Y. W., & Santos, R. M. (2020). Risk assessment of Ni, Cr, and Si release from alkaline minerals during enhanced weathering. *Open Agriculture*, *5*(1), 166. https://doi.org/10.1515/opag-2020-0016

Haque, F., Santos, R. M., & Chiang, Y. W. (2020a). CO_2 sequestration by wollastonite-amended agricultural soils—An Ontario field study. *International Journal of Greenhouse Gas Control*, *97*, 103017. https://doi.org/10.1016/j.ijggc.2020.103017

Haque, F., Santos, R. M., & Chiang, Y. W. (2020b). Optimizing inorganic carbon sequestration and crop yield with wollastonite soil amendment in a microplot study. *Frontiers in Plant Science*, *11*(1012). https://doi.org/10.3389/fpls.2020.01012

Haque, F., Santos, R. M., Dutta, A., Thimmanagari, M., & Chiang, Y. W. (2019). Co-benefits of wollastonite weathering in agriculture: CO_2 sequestration and promoted plant growth. *ACS Omega*, *4*(1), 1425–1433. https://doi.org/10.1021/acsomega.8b02477

Harley, A. D., & Gilkes, R. J. (2000). Factors influencing the release of plant nutrient elements from silicate rock powders: A geochemical overview. *Nutrient Cycling in Agroecosystems*, *56*(1), 11–36. https://doi.org/10.1023/A:1009859309453

Hartmann, J., West, A. J., Renforth, P., Köhler, P., De La Rocha, C. L., Wolf-Gladrow, D. A., Dürr, H. H., & Scheffran, J. (2013). Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Reviews of Geophysics*, *51*(2), 113–149. https://doi.org/10.1002/rog.20004

Haynes, R. J. (2014). A contemporary overview of silicon availability in agricultural soils. *Journal of Plant Nutrition and Soil Science*, *177*(6), 831–844. https://doi.org/10.1002/jpln.201400202

Hénault, C., Bourennane, H., Ayzac, A., Ratié, C., Saby, N. P. A., Cohan, J.-P., Eglin, T., & Gall, C. L. (2019). Management of soil pH promotes nitrous oxide reduction and thus mitigates soil emissions of this greenhouse gas. *Scientific Reports*, *9*(1), 20182. https://doi.org/10.1038/s41598-019-56694-3

Hilaire, J., Minx, J. C., Callaghan, M. W., Edmonds, J., Luderer, G., Nemet, G. F., Rogelj, J., & del Mar Zamora, M. (2019). Negative emissions and international climate goals—learning from and about mitigation scenarios. *Climatic Change*, *157*(2), 189–219. https://doi.org/10.1007/s10584-019-02516-4

Hinsinger, P. (1998). How do plant roots acquire mineral nutrients? Chemical processes involved in the rhizosphere. *Advances in Agronomy*, *64*, 225–265.

Hinsinger, P., Fernandes Barros, O. N., Benedetti, M. F., Noack, Y., & Callot, G. (2001). Plant-induced weathering of a basaltic rock: Experimental evidence. *Geochimica et Cosmochimica Acta*, *65*(1), 137–152. https://doi.org/10.1016/S0016-7037(00)00524-X

Hodson, M. J., White, P. J., Mead, A., & Broadley, M. R. (2005). Phylogenetic variation in the silicon composition of plants. *Annals of Botany*, *96*(6), 1027–1046. https://doi.org/10.1093/aob/mci255

Howard, R. J., Ferrari, M. A., Roach, D. H., & Money, N. P. (1991). Penetration of hard substrates by a fungus employing enormous turgor pressures. *Proceedings of the National Academy of Sciences of the United States of America*, *88*(24), 11281–11284. https://doi.org/10.1073/pnas.88.24.11281

Hu, H.-W., Chen, D., & He, J.-Z. (2015). Microbial regulation of terrestrial nitrous oxide formation: Understanding the biological pathways for prediction of emission rates. *FEMS Microbiology Reviews*, *39*(5), 729–749. https://doi.org/10.1093/femsre/fuv021

Hu, L., Xia, M., Lin, X., Xu, C., Li, W. U., Wang, J., Zeng, R., & Song, Y. (2018). Earthworm gut bacteria increase silicon bioavailability and acquisition by maize. *Soil Biology and Biochemistry*, *125*, 215–221. https://doi.org/10.1016/j.soilbio.2018.07.015

IPCC. (2018). *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (P. Z. V. Masson-Delmotte, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, & T. Waterfield, Eds.). World Meteorological Organization.

IPCC. (2021). *Climate change 2021: The physical science basis. contribution of working group i to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge University Press.

Ireland, M. P. (1983). Heavy metal uptake and tissue distribution in earthworms. In J. E. Satchell (Ed.), *Earthworm ecology: From Darwin to Vermiculture* (pp. 247–265). Springer, Netherlands.

Kelland, M. E., Wade, P. W., Lewis, A. L., Taylor, L. L., Sarkar, B., Andrews, M. G., & Beerling, D. J. (2020). Increased yield and CO_2 sequestration potential with the C4 cereal Sorghum bicolor cultivated in basaltic rock dust-amended agricultural soil. *Global Change Biology*, *26*(6), 3658–3676. https://doi.org/10.1111/gcb.15089

Khoshgoftarmanesh, A. H., Hosseini, F., & Afyuni, M. (2011). Nickel supplementation effect on the growth, urease activity and urea and nitrate concentrations in lettuce supplied with different nitrogen sources. *Scientia Horticulturae*, *130*(2), 381–385. https://doi.org/10.1016/j.scienta.2011.07.009

Kidder, D. L., & Gierlowski-Kordesch, E. H. (2005). Impact of grassland radiation on the nonmarine silica cycle and Miocene diatomite. *Palaios*, *20*(2), 198–206. https://doi.org/10.2110/palo.2003.p03-108

Kim, W.-J., Bui, L. T., Chun, J.-B., McClung, A. M., & Barnaby, J. Y. (2018). Correlation between methane (CH_4) emissions and root aerenchyma of rice varieties. *Plant Breeding and Biotechnology*, *6*(4), 381–390.

Köhler, P., Hartmann, J., & Wolf-Gladrow, D. A. (2010). Geoengineering potential of artificially enhanced silicate weathering of olivine. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(47), 20228–20233. https://doi.org/10.1073/pnas.1000545107

Korndörfer, G., & Lepsch, I. (2001). Effect of silicon on plant growth and crop yield. In L. E. Datnoff, G. H. Snyder, & G. H. Korndörfer (Eds.), *Studies in plant science* (Vol. *8*, pp. 133–147). Elsevier.

Krishnapriya, V., & Pandey, R. (2016). Root exudation index: Screening organic acid exudation and phosphorus acquisition efficiency in soybean genotypes. *Crop and Pasture Science*, *67*(10), 1096–1109. https://doi.org/10.1071/CP15329

Ku, H.-H., Hayashi, K., Agbisit, R., & Villegas-Pangga, G. (2020). Effect of calcium silicate on nutrient use of lowland rice and greenhouse gas emission from a paddy soil under alternating wetting and drying. *Pedosphere*, *30*(4), 535–543. https://doi.org/10.1016/S1002-0160(17)60401-6

Kumar, O., Singh, S. K., Singh, A. P., Yadav, S. N., & Latare, A. M. (2018). Effect of soil application of nickel on growth, micronutrient concentration and uptake in barley (*Hordeum vulgare* L.) grown in Inceptisols of Varanasi. *Journal of Plant Nutrition*, *41*(1), 50–66. https://doi.org/10.1080/01904167.2017.1381724

Lambkin, D. C., Gwilliam, K., Layton, C., Canti, M., Piearce, T., & Hodson, M. E. (2011). Soil pH governs production rate of calcium carbonate secreted by the earthworm *Lumbricus terrestris*. *Applied Geochemistry*, *26*, S64–S66. https://doi.org/10.1016/j.apgeochem.2011.03.032

Lehmann, A., Zheng, W., & Rillig, M. C. (2017). Soil biota contributions to soil aggregation. *Nature Ecology & Evolution*, *1*(12), 1828–1835. https://doi.org/10.1038/s41559-017-0344-y

Leifeld, J., Bassin, S., Conen, F., Hajdas, I., Egli, M., & Fuhrer, J. (2013). Control of soil pH on turnover of belowground organic matter in subalpine grassland. *Biogeochemistry*, *112*(1), 59–69. https://doi.org/10.1007/s10533-011-9689-5

Lenzewski, N., Mueller, P., Meier, R. J., Liebsch, G., Jensen, K., & Koop-Jakobsen, K. (2018). Dynamics of oxygen and carbon dioxide in rhizospheres of *Lobelia dortmanna*—A planar optode study of belowground gas exchange between plants and sediment. *New Phytologist*, *218*(1), 131–141. https://doi.org/10.1111/nph.14973

Leonardos, O. H., Fyfe, W. S., & Kronberg, B. I. (1987). The use of ground rocks in laterite systems: An improvement to the use of conventional soluble fertilizers? *Chemical Geology*, *60*(1), 361–370. https://doi.org/10.1016/0009-2541(87)90143-4

Liang, Y., Nikolic, M., Bélanger, R., Gong, H., & Song, A. (2015). Silicon in agriculture. In Y. Liang, M. Nikolic, R. Bélanger, H. Gong, & A. Song (Eds.), *Silicon-mediated tolerance to salt stress* (pp. 123–142). Springer Science.

Likens, G. E. (2017). Fifty years of continuous precipitation and stream chemistry data from the Hubbard Brook ecosystem study (1963–2013). *Ecology*, *98*(8), 2224. https://doi.org/10.1002/ecy.1894

Litton, C. M., Raich, J. W., & Ryan, M. G. (2007). Carbon allocation in forest ecosystems. *Global Change Biology*, *13*(10), 2089–2109. https://doi.org/10.1111/j.1365-2486.2007.01420.x

Liu, B., Mørkved, P. T., Frostegård, Å., & Bakken, L. R. (2010). Denitrification gene pools, transcription and kinetics of NO, N_2O and N_2 production as affected by soil pH. *Fems Microbiology Ecology*, *72*(3), 407–417.

Liu, D. F., Lian, B., Wang, B., & Jiang, G. F. (2011). Degradation of potassium rock by earthworms and responses of bacterial communities in its gut and surrounding substrates after being fed with mineral. *PLoS One*, *6*(12), 17. https://doi.org/10.1371/journal.pone.0028803

Liu, X., Zhang, M., Li, Z., Zhang, C., Wan, C., Zhang, Y., & Lee, D.-J. (2019). Inhibition of urease activity by humic acid extracted from sludge fermentation liquid. *Bioresource Technology*, *290*, 121767. https://doi.org/10.1016/j.biortech.2019.121767

Lubbers, I. M., van Groenigen, K. J., Fonte, S. J., Six, J., Brussaard, L., & van Groenigen, J. W. (2013). Greenhouse-gas emissions from soils increased by earthworms. *Nature Climate Change*, *3*(3), 187–194. https://doi.org/10.1038/nclimate1692

Lundström, U. S., Bain, D. C., Taylor, A. F. S., & van Hees, P. A. W. (2003). Effects of acidification and its mitigation with lime and wood ash on forest soil processes: A review. *Water, Air and Soil Pollution: Focus*, *3*(4), 5–28. https://doi.org/10.1023/A:1024115111377

Ma, W.-C. (1988). Toxicity of copper to lumbricid earthworms in sandy agricultural soils amended with cu-enriched organic waste materials. *Ecological Bulletins*, *39*, 53–56.

Melvin, A. M., Lichstein, J. W., & Goodale, C. L. (2013). Forest liming increases forest floor carbon and nitrogen stocks in a mixed hardwood forest. *Ecological Applications*, *23*(8), 1962–1975. https://doi.org/10.1890/13-0274.1

Mersi, W. V., Kuhnert-Finkernagel, R., & Schinner, F. (1992). The influence of rock powders on microbial activity of three forest soils. *Zeitschrift für Pflanzenernährung und Bodenkunde*, *155*(1), 29–33. https://doi.org/10.1002/jpln.19921550107

Mira, A., Cantarella, H., Souza-Netto, G., Moreira, L., Kamogawa, M., & Otto, R. (2017). Optimizing urease inhibitor usage to reduce ammonia emission following urea application over crop residues. *Agriculture, Ecosystems & Environment*, *248*, 105–112. https://doi.org/10.1016/j.agee.2017.07.032

Moghal, A. A. B., Lateef, M. A., Abu Sayeed Mohammed, S., Ahmad, M., Usman, A. R. A., & Almajed, A. (2020). Heavy metal immobilization studies and enhancement in geotechnical properties of cohesive soils by EICP technique. *Applied Sciences*, *10*(21), 7568. https://doi.org/10.3390/app10217568

Munevar, F., & Romero, A. (2015). Soil and plant silicon status in oil palm crops in Colombia. *Experimental Agriculture*, *51*(3), 382. https://doi.org/10.1017/S0014479714000374

Nadeem, S., Bakken, L. R., Frostegård, Å., Gaby, J. C., & Dörsch, P. (2020). Contingent effects of liming on N_2O-emissions driven by autotrophic nitrification. *Frontiers in Environmental Science*, *8*(245). https://doi.org/10.3389/fenvs.2020.598513

Nebert, L. D., Bloem, J., Lubbers, I. M., & van Groenigen, J. W. (2011). Association of earthworm-denitrifier interactions with increased emission of nitrous oxide from soil mesocosms amended with crop residue. *Applied and Environmental Microbiology*, *77*(12), 4097–4104. https://doi.org/10.1128/AEM.00033-11

Neu, S., Schaller, J., & Dudel, E. G. (2017). Silicon availability modifies nutrient use efficiency and content, C:N:P stoichiometry, and productivity of winter wheat (*Triticum aestivum* L.). *Scientific Reports*, *7*(1), 40829. https://doi.org/10.1038/srep40829

Obersteiner, M., Bednar, J., Wagner, F., Gasser, T., Ciais, P., Forsell, N., Frank, S., Havlik, P., Valin, H., Janssens, I. A., Peñuelas, J., & Schmidt-Traub, G. (2018). How to spend a dwindling greenhouse gas budget. *Nature Climate Change*, *8*(1), 7–10. https://doi.org/10.1038/s41558-017-0045-1

Oelkers, E. H., Benning, L. G., Lutz, S., Mavromatis, V., Pearce, C. R., & Plümper, O. (2015). The efficient long-term inhibition of forsterite dissolution by common soil bacteria and fungi at Earth surface conditions. *Geochimica et Cosmochimica Acta*, *168*, 222–235. https://doi.org/10.1016/j.gca.2015.06.004

Oliveira, T. C., Fontes, R. L. F., Rezende, S. T. D., & Víctor Hugo, A. V. (2013). Effects of nickel and nitrogen soil fertilization on lettuce growth and urease activity. *Revista Brasileira de Ciência do Solo*, *37*, 698–706. https://doi.org/10.1590/S0100-06832013000300016

Or, D., Keller, T., & Schlesinger, W. H. (2021). Natural and managed soil structure: On the fragile scaffolding for soil functioning. *Soil and Tillage Research*, *208*, 104912. https://doi.org/10.1016/j.still.2020.104912

Palandri, J. L., & Kharaka, Y. K. (2004). *A compilation of rate parameters of water-mineral interaction kinetics for application to geochemical modeling*. U.S. geological survey, open file report 2004-1068.

Paradelo, R., Virto, I., & Chenu, C. (2015). Net effect of liming on soil organic carbon stocks: A review. *Agriculture, Ecosystems & Environment*, *202*, 98–107. https://doi.org/10.1016/j.agee.2015.01.005

Persson, T., Andersson, S., Bergholm, J., Grönqvist, T., Högbom, L., Vegerfors, B., & Wirén, A. (2021). Long-term impact of liming on soil C and N in a fertile spruce forest ecosystem. *Ecosystems*, *24*(4), 968–987. https://doi.org/10.1007/s10021-020-00563-y

Peters, S. C., Blum, J. D., Driscoll, C. T., & Likens, G. E. (2004). Dissolution of wollastonite during the experimental manipulation of Hubbard Brook Watershed 1. *Biogeochemistry*, *67*(3), 309–329. https://doi.org/10.1023/B:BIOG.0000015787.44175.3f

Poorter, H., Niklas, K. J., Reich, P. B., Oleksyn, J., Poot, P., & Mommer, L. (2012). Biomass allocation to leaves, stems and roots: Meta-analyses of interspecific variation and environmental control. *New Phytologist*, *193*(1), 30–50. https://doi.org/10.1111/j.1469-8137.2011.03952.x

Psarras, P., Krutka, H., Fajardy, M., Zhang, Z., Liguori, S., Dowell, N. M., & Wilcox, J. (2017). Slicing the pie: How big could carbon dioxide removal be? *Wiley Interdisciplinary Reviews: Energy and Environment*, *6*(5), e253. https://doi.org/10.1002/wene.253

Reddy, K. R., Gopakumar, A., & Chetri, J. K. (2019). Critical review of applications of iron and steel slags for carbon sequestration and environmental remediation. *Reviews in Environmental Science and Bio/Technology*, *18*(1), 127–152. https://doi.org/10.1007/s11157-018-09490-w

Reith, F., Zammit, C. M., Pohrib, R., Gregg, A. L., & Wakelin, S. A. (2015). Geogenic factors as drivers of microbial community diversity in soils overlying polymetallic deposits. *Applied and Environmental Microbiology*, *81*(22), 7822–7832. https://doi.org/10.1128/aem.01856-15

Rinder, T., & von Hagke, C. (2021). The influence of particle size on the potential of enhanced basalt weathering for carbon dioxide removal—Insights from a regional assessment. *Journal of Cleaner Production*, *315*, 128178. https://doi.org/10.1016/j.jclepro.2021.128178

Rockström, J., Gaffney, O., Rogelj, J., Meinshausen, M., Nakicenovic, N., & Schellnhuber, H. J. (2017). A roadmap for rapid decarbonization. *Science*, *355*(6331), 1269–1271. https://doi.org/10.1126/science.aah3443

Ros, M. B. H., Hiemstra, T., van Groenigen, J. W., Chareesri, A., & Koopmans, G. F. (2017). Exploring the pathways of earthworm-induced phosphorus availability. *Geoderma*, *303*, 99–109. https://doi.org/10.1016/j.geoderma.2017.05.012

Rowley, M. C., Grand, S., Spangenberg, J. E., & Verrecchia, E. P. (2021). Evidence linking calcium to increased organo-mineral association in soils. *Biogeochemistry*, *153*(3), 223–241. https://doi.org/10.1007/s10533-021-00779-7

Rowley, M. C., Grand, S., & Verrecchia, É. P. (2018). Calcium-mediated stabilisation of soil organic carbon. *Biogeochemistry*, *137*(1), 27–49. https://doi.org/10.1007/s10533-017-0410-1

Ryan, P. R., Delhaize, E., & Jones, D. L. (2001). Function and mechanism of organic anion exudation from plant roots. *Annual Review of Plant Physiology and Plant Molecular Biology*, *52*, 527–560. https://doi.org/10.1146/annurev.arplant.52.1.527

Saunois, M., Stavert, A. R., Poulter, B., Bousquet, P., Canadell, J. G., Jackson, R. B., Raymond, P. A., Dlugokencky, E. J., Houweling, S., Patra, P. K., Ciais, P., Arora, V. K., Bastviken, D., Bergamaschi, P., Blake, D. R., Brailsford, G., Bruhwiler, L., Carlson, K. M., Carrol, M., … Zhuang, Q. (2020). The global methane budget 2000–2017. *Earth System Science Data*, *12*(3), 1561–1623. https://doi.org/10.5194/essd-12-1561-2020

Schmidt, M. W. I., Torn, M. S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I. A., Kleber, M., Kögel-Knabner, I., Lehmann, J., Manning, D. A. C., Nannipieri, P., Rasse, D. P., Weiner, S., & Trumbore, S. E. (2011). Persistence of soil organic matter as an ecosystem property. *Nature*, *478*(7367), 49–56. https://doi.org/10.1038/nature10386

Schuiling, R. D., & Krijgsman, P. (2006). Enhanced weathering: An effective and cheap tool to sequester CO_2. *Climatic Change*, *74*(1–3), 349–354. https://doi.org/10.1007/s10584-005-3485-y

Schwartzman, D. W., & Volk, T. (1989). Biotic enhancement of weathering and the habitability of Earth. *Nature*, *340*(6233), 457–460. https://doi.org/10.1038/340457a0

Shipitalo, M. J., & Protz, R. (1989). Chemistry and micromorphology of aggregation in earthworm casts. *Geoderma*, *45*(3), 357–374. https://doi.org/10.1016/0016-7061(89)90016-5

Silva, D. R. G., Marchi, G., Spehar, C. R., Guilherme, L. R. G., Rein, T. A., Soares, D. A., & Ávila, F. W. (2012). Characterization and nutrient release from silicate rocks and influence on chemical changes in soil. *Revista Brasileira de Ciência do Solo*, *36*(3), 951–962. https://doi.org/10.1590/S0100-06832012000300025

Sinsabaugh, R. L., Lauber, C. L., Weintraub, M. N., Ahmed, B., Allison, S. D., Crenshaw, C., Contosta, A. R., Cusack, D., Frey, S., Gallo, M. E., Gartner, T. B., Hobbie, S. E., Holland, K., Keeler, B. L., Powers, J. S., Stursova, M., Takacs-Vesbach, C., Waldrop, M. P., Wallenstein, M. D., … Zeglin, L. H. (2008). Stoichiometry of soil enzyme activity at global scale. *Ecology Letters*, *11*(11), 1252–1264. https://doi.org/10.1111/j.1461-0248.2008.01245.x

Storer, K., Coggan, A., Ineson, P., & Hodge, A. (2018). Arbuscular mycorrhizal fungi reduce nitrous oxide emissions from N_2O hotspots. *New Phytologist*, *220*(4), 1285–1295. https://doi.org/10.1111/nph.14931

Strefler, J., Amann, T., Bauer, N., Kriegler, E., & Hartmann, J. (2018). Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environmental Research Letters*, *13*(3), 034010. https://doi.org/10.1088/1748-9326/aaa9c4

Sun, L., Xiao, L., Xiao, B., Wang, W., Pan, C., Wang, S., & Lian, B. (2013). Differences in the gene expressive quantities of carbonic anhydrase and cysteine synthase in the weathering of potassium-bearing minerals by *Aspergillus niger*. *Science China Earth Sciences*, *56*(12), 2135–2140. https://doi.org/10.1007/s11430-013-4704-4

Swoboda, P., Döring, T. F., & Hamer, M. (2021). Remineralizing soils? The agricultural usage of silicate rock powders: A review. *Science of the Total Environment*, 150976. https://doi.org/10.1016/j.scitotenv.2021.150976

Taylor, L. L., Driscoll, C. T., Groffman, P. M., Rau, G. H., Blum, J. D., & Beerling, D. J. (2021). Increased carbon capture by a silicate-treated forested watershed affected by acid deposition. *Biogeosciences*, *18*(1), 169–188. https://doi.org/10.5194/bg-18-169-2021

Terrer, C., Jackson, R. B., Prentice, I. C., Keenan, T. F., Kaiser, C., Vicca, S., Fisher, J. B., Reich, P. B., Stocker, B. D., Hungate, B. A., Peñuelas, J., McCallum, I., Soudzilovskaia, N. A., Cernusak, L. A., Talhelm, A. F., Van Sundert, K., Piao, S., Newton, P. C. D., Hovenden, M. J., … Franklin, O. (2019). Nitrogen and phosphorus constrain the CO_2 fertilization of global plant biomass. *Nature Climate Change*, *9*(9), 684–689. https://doi.org/10.1038/s41558-019-0545-2

Terrer, C., Phillips, R. P., Hungate, B. A., Rosende, J., Pett-Ridge, J., Craig, M. E., van Groenigen, K. J., Keenan, T. F., Sulman, B. N., Stocker, B. D., Reich, P. B., Pellegrini, A. F. A., Pendall, E., Zhang, H., Evans, R. D., Carrillo, Y., Fisher, J. B., Van Sundert, K., Vicca, S., & Jackson, R. B. (2021). A trade-off between plant and soil carbon storage under elevated CO_2. *Nature*, *591*(7851), 599–603. https://doi.org/10.1038/s41586-021-03306-8

Thomas, E., Prabha, V. S., Kurien, V. T., & Thomas, A. (2020). The potential of earthworms in soil carbon storage: A review. *Environmental and Experimental Biology*, *18*, 61–75. https://doi.org/10.22364/eeb.18.06

Tian, H., Xu, R., Canadell, J. G., Thompson, R. L., Winiwarter, W., Suntharalingam, P., Davidson, E. A., Ciais, P., Jackson, R. B., Janssens-Maenhout, G., Prather, M. J., Regnier, P., Pan, N., Pan, S., Peters, G. P., Shi, H., Tubiello, F. N., Zaehle, S., Zhou, F., … Yao, Y. (2020). A comprehensive quantification of global nitrous oxide sources and sinks. *Nature*, *586*(7828), 248–256. https://doi.org/10.1038/s41586-020-2780-0

Tosi, M., Brown, S., Machado, P. V. F., Wagner-Riddle, C., & Dunfield, K. (2020). Short-term response of soil N-cycling genes and transcripts to fertilization with nitrification and urease inhibitors, and relationship with field-scale N_2O emissions. *Soil Biology and Biochemistry*, *142*, 107703. https://doi.org/10.1016/j.soilbio.2019.107703

UNFCCC. (2015). *Adoption of the Paris agreement*. Proposal by the President.

Van Bockhaven, J., De Vleesschauwer, D., & Höfte, M. (2013). Towards establishing broad-spectrum disease resistance in plants: Silicon leads the way. *Journal of Experimental Botany*, *64*(5), 1281–1293. https://doi.org/10.1093/jxb/ers329

Van Groenigen, J. W., Van Groenigen, K. J., Koopmans, G. F., Stokkermans, L., Vos, H. M. J., & Lubbers, I. M. (2019). How fertile are earthworm casts? A meta-analysis. *Geoderma*, *338*, 525–535. https://doi.org/10.1016/j.geoderma.2018.11.001

Van Hees, P. A., Rosling, A., Essén, S., Godbold, D. L., Jones, D. L., & Finlay, R. D. (2006). Oxalate and ferricrocin exudation by the extramatrical mycelium of an ectomycorrhizal fungus in symbiosis with *Pinus sylvestris*. *New Phytologist*, *169*(2), 367–378. https://doi.org/10.1111/j.1469-8137.2005.01600.x

Van Straaten, P. (2006). Farming with rocks and minerals: Challenges and opportunities. *Anais da Academia Brasileira de Ciências*, *78*, 731–747. https://doi.org/10.1590/S0001-37652006000400009

Van Sundert, K., Linder, S., Marshall, J. D., Nordin, A., & Vicca, S. (2020). Increased tree growth following long-term optimised fertiliser application indirectly alters soil properties in a boreal forest. *European Journal of Forest Research*. https://doi.org/10.1007/s10342-020-01327-y

Ven, A., Verlinden, M. S., Fransen, E., Olsson, P. A., Verbruggen, E., Wallander, H., & Vicca, S. (2020). Phosphorus addition increased carbon partitioning to autotrophic respiration but not to biomass production in an experiment with *Zea mays*. *Plant, Cell & Environment*, *43*(9), 2054–2065. https://doi.org/10.1111/pce.13785

Ven, A., Verlinden, M. S., Verbruggen, E., & Vicca, S. (2019). Experimental evidence that phosphorus fertilization and arbuscular mycorrhizal symbiosis can reduce the carbon cost of phosphorus uptake. *Functional Ecology*, *33*(11), 2215–2225. https://doi.org/10.1111/1365-2435.13452

Verbruggen, E., Struyf, E., & Vicca, S. (2021). Can arbuscular mycorrhizal fungi speed up carbon sequestration by enhanced weathering? *Plants, People, Planet*, *3*, 445–453. https://doi.org/10.1002/ppp3.10179

Verlinden, M. S., Ven, A., Verbruggen, E., Janssens, I. A., Wallander, H., & Vicca, S. (2018). Favorable effect of mycorrhizae on biomass production efficiency exceeds their carbon cost in a fertilization experiment. *Ecology*, *99*(11), 2525–2534. https://doi.org/10.1002/ecy.2502

Versteegh, E. A. A., Black, S., & Hodson, M. E. (2014). Environmental controls on the production of calcium carbonate by earthworms. *Soil Biology and Biochemistry*, *70*, 159–161. https://doi.org/10.1016/j.soilbio.2013.12.013

Vicca, S., Luyssaert, S., Peñuelas, J., Campioli, M., Chapin, F. S., Ciais, P., Heinemeyer, A., Högberg, P., Kutsch, W. L., Law, B. E., Malhi, Y., Papale, D., Piao, S. L., Reichstein, M., Schulze, E. D., & Janssens, I. A. (2012). Fertile forests produce biomass more efficiently. *Ecology Letters*, *15*(6), 520–526. https://doi.org/10.1111/j.1461-0248.2012.01775.x

Vicca, S., Stocker, B. D., Reed, S., Wieder, W. R., Bahn, M., Fay, P. A., Janssens, I. A., Lambers, H., Peñuelas, J., Piao, S., Rebel, K. T., Sardans, J., Sigurdsson, B. D., Van Sundert, K., Wang, Y.-P., Zaehle, S., & Ciais, P. (2018). Using research networks to create the comprehensive datasets needed to assess nutrient availability as a key determinant of terrestrial carbon cycling. *Environmental Research Letters*, *13*(12), 125006. https://doi.org/10.1088/1748-9326/aaeae7

Viles, H. A., Goudie, A. S., & Goudie, A. M. (2021). Ants as geomorphological agents: A global assessment. *Earth-Science Reviews*, *213*, 103469. https://doi.org/10.1016/j.earscirev.2020.103469

Walker, J. C. G., Hays, P. B., & Kasting, J. F. (1981). A negative feedback mechanism for the long-term stabilization of Earth's surface temperature. *Journal of Geophysical Research: Oceans*, *86*(C10), 9776–9782. https://doi.org/10.1029/JC086iC10p09776

Wang, C., Wang, W., Sardans, J., Singla, A., Zeng, C., Lai, D. Y. F., & Peñuelas, J. (2018). Effects of steel slag and biochar amendments on CO_2, CH_4, and N_2O flux, and rice productivity in a subtropical Chinese paddy field. *Environmental Geochemistry and Health*. https://doi.org/10.1007/s10653-018-0224-7

Wang, G., Xia, X., Yang, J., Tariq, M., Zhao, J., Zhang, M., Huang, K., Lin, K., & Zhang, W. (2020). Exploring the bioavailability of nickel in a soil system: Physiological and histopathological toxicity study to the earthworms (*Eisenia fetida*). *Journal of Hazardous Materials*, *383*, 121169. https://doi.org/10.1016/j.jhazmat.2019.121169

Wang, H., Köbke, S., & Dittert, K. (2020). Use of urease and nitrification inhibitors to reduce gaseous nitrogen emissions from fertilizers containing ammonium nitrate and urea. *Global Ecology and Conservation*, *22*, e00933. https://doi.org/10.1016/j.gecco.2020.e00933

Wang, W., Zeng, C., Sardans, J., Zeng, D., Wang, C., Bartrons, M., & Penuelas, J. (2018). Industrial and agricultural wastes decreased greenhouse gas emissions and increased rice grain yield in a subtropical paddy field. *Experimental Agriculture*, *54*(4), 623–640. https://doi.org/10.1017/s001447971700031x

Wild, B., Imfeld, G., & Daval, D. (2021). Direct measurement of fungal contribution to silicate weathering rates in soil. *Geology*. https://doi.org/10.1130/g48706.1

Xiao, B., Lian, B., Sun, L., & Shao, W. (2012). Gene transcription response to weathering of K-bearing minerals by *Aspergillus fumigatus*. *Chemical Geology*, *306–307*, 1–9. https://doi.org/10.1016/j.chemgeo.2012.02.014

Xiao, L., Lian, B., Hao, J., Liu, C., & Wang, S. (2015). Effect of carbonic anhydrase on silicate weathering and carbonate formation at present day CO_2 concentrations compared to primordial values. *Scientific Reports*, *5*(1), 7733. https://doi.org/10.1038/srep07733

Zaharescu, D. G., Burghelea, C. I., Dontsova, K., Reinhard, C. T., Chorover, J., & Lybrand, R. (2020). Biological weathering in the terrestrial system. In *Biogeochemical cycles* (pp. 1–32).

Zaihua, L. (2001). Role of carbonic anhydrase as an activator in carbonate rock dissolution and its implication for atmospheric CO_2 sink. *Acta Geologica Sinica-English Edition*, *75*(3), 275–278. https://doi.org/10.1111/j.1755-6724.2001.tb00531.x

Zamanian, K., Pustovoytov, K., & Kuzyakov, Y. (2016). Pedogenic carbonates: Forms and formation processes. *Earth-Science Reviews*, *157*, 1–17. https://doi.org/10.1016/j.earscirev.2016.03.003

Zhang, G., Kang, J., Wang, T., & Zhu, C. (2018). Review and outlook for agromineral research in agriculture and climate mitigation. *Soil Research*, *56*(2), 113–122. https://doi.org/10.1071/SR17157

Zhang, H., & Bloom, P. R. (1999). Dissolution kinetics of hornblende in organic acid solutions. *Soil Science Society of America Journal*, *63*(4), 815–822. https://doi.org/10.2136/sssaj1999.634815x

Zhou, X., Shen, Y., Fu, X., & Wu, F. (2018). Application of sodium silicate enhances cucumber resistance to fusarium wilt and alters soil microbial communities. *Frontiers in Plant Science*, *9*(624). https://doi.org/10.3389/fpls.2018.00624

Zhu, X., Lian, B., Yang, X., Liu, C., & Zhu, L. (2013). Biotransformation of earthworm activity on potassium-bearing mineral powder. *Journal of Earth Science*, *24*(1), 65–74. https://doi.org/10.1007/s12583-013-0313-6

How to cite this article: Vicca, S., Goll, D. S., Hagens, M., Hartmann, J., Janssens, I. A., Neubeck, A., Peñuelas, J., Poblador, S., Rijnders, J., Sardans, J., Struyf, E., Swoboda, P., van Groenigen, J. W., Vienne, A., & Verbruggen, E. (2021). Is the climate change mitigation effect of enhanced silicate weathering governed by biological processes? *Global Change Biology*, 00, 1–16. https://doi.org/10.1111/gcb.15993