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Applying minerals to soil to draw down atmospheric carbon dioxide through synergistic organic and inorganic pathways



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Minerals in soil can sequester atmospheric carbon dioxide through natural organic and inorganic processes. Here we consider three soil- and mineral-based methods for carbon dioxide removal: (1) grinding and spreading of calcium- and magnesium-rich silicate rocks for enhanced rock weathering and subsequent inorganic carbon formation, (2) mineral doping of biomass prior to conversion into biochar for enhanced biochar carbon yield and stability, and (3) strategic application of minerals to soil to increase soil organic carbon accrual and stability. We argue that there are powerful synergies between these approaches for carbon dioxide removal through organic and inorganic pathways. We find that primary silicates, as contained in basalt, can benefit both enhanced weathering and soil organic carbon formation, while phyllosilicates and other reactive secondary minerals may have positive synergies for biochar and soil organic carbon. Optimising such synergies may substantially enhance economic and environmental benefits, yet these synergies require accurate quantification.

To mitigate the severe environmental and economic impacts of climate change, it is critical to reduce global warming to below 2 °C, as recommended by the Paris Agreement¹. Climate change and associated temperature extremes, droughts and flooding threaten global food production, the long-term sustainability of human civilization, and the entire biosphere². In addition to decarbonizing the global economy, it is now necessary to also achieve carbon dioxide removal (CDR) of around 10 Gt CO₂ per year by 2050 to keep planetary warming below 2 °C^{3,4}. CDR is required both to remove excess atmospheric CO₂, and to offset emissions that cannot be easily abated⁵. However, the CDR industry has struggled to grow, as individual CDR methods are hindered by economic barriers, as well as social and political limitations. Acceleration of CDR implementation is essential to limit global warming to a mean increase of 2 °C relative to the pre-industrial era³. Therefore, there is a need to enhance the efficacy and potential of CDR methods and their co-benefits, which can partly be achieved by integrating different methods to improve economic and environmental outcomes^{6,7}.

Several CDR methods function by enhancing natural biogeochemical cycles that remove and sequester CO₂ from the atmosphere^{8–12}. Minerals play a key role in several of such methods, through interactions with carbon in soil (including inorganic carbon, soil organic matter and plant biomass)

that result in CDR^{7,13}. Here, we describe three soil-based CDR approaches that use minerals, namely: (A) inorganic carbon storage through the application of crushed silicate minerals to soil (enhanced rock weathering), (B) mineral ‘doping’ of biochar, to store persistent pyrolyzed, organic carbon, and (C) accrual of soil organic carbon through additions of reactive minerals.

In brief, these three processes occur as follows: (A) During weathering of calcium (Ca)- and magnesium (Mg)-rich silicate minerals, CO₂ is removed from the atmosphere and stored as dissolved inorganic carbon in the Earth’s soils, subsurface geological deposit, waterways, and oceans. This natural process results in ~0.5 Gt of CO₂ drawdown annually¹⁴. Through enhanced rock weathering – i.e. the deliberate crushing and subsequent spreading of silicate dust – between 0.5 and 2 Gt of additional CO₂ could be removed^{15–17}, or 5–20% of the CDR needed by 2050^{3,4}.

(B) When plant biomass is turned into pyrogenic carbon under high temperatures and low oxygen levels, i.e., during fires, the pyrolyzed material can persist for long timescales in soil¹⁸. This material is termed biochar when it is intentionally produced for the purpose of environmental management. Biochar production has the potential to remove 0.03–6.6 Gt of CO₂ per year¹⁹. During pyrogenic carbon/biochar formation, minerals can enhance

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carbon retention and persistence; i.e., biomass with higher mineral contents produces biochar that comprises a greater proportion of organic carbon in persistent fractions²⁰. Biomass can be doped intentionally with minerals to enhance this effect⁷.

(C) Organic carbon storage in soils (as soil organic matter; SOM) can persist over long time scales through interactions with soil minerals, which limit oxygen and microbial access to this material. SOM is the largest terrestrial carbon pool (~1500 Gt of carbon equivalents) and the most persistent fractions are mineral-associated and aggregated organic matter^{21,22}. To increase the SOM stock, it is possible to increase organic inputs to soils, or to enhance the capacity of soil to retain more persistent forms of SOM. The latter may be achieved via mineral amendments of soils, though this method that has yet to be quantitatively assessed in the field. However, the total potential for SOM accrual globally (all land uses) is estimated at 0.4–8.6 Gt CO₂ per year¹⁹.

To date, these different mineral-based CDR methods that are applied to soil have mostly been researched separately^{7,23,24}, even though there are strong potential synergies between them (see Fig. 1). In this perspective article, we describe such potential synergies between these three CDR methods – describing both how they work as well as some of their limitations (Section 2). Next, we discuss general mineral properties and environmental conditions that enable and optimise synergies between these methods (Section 3).

Finally, we discuss the suitability of a variety of minerals for each CDR method, and identify potential minerals that may be suitable for sequestering carbon through multiple CDR methods (Section 4).

Individual CDR methods

Enhanced weathering (EW) of Ca- and Mg-rich silicate rocks

Natural processes weather rock on geological time scales, driving long-term variations in atmospheric CO₂ levels, and removing ~0.5 Gt of CO₂ from the atmosphere per year^{25,26}. Physical weathering causes rock to be broken apart; during chemical weathering, Ca- and Mg-rich silicate rocks react with carbonic acid (CO₂ dissolved in water), ultimately stabilising the dissolved CO₂ in the form of bicarbonate and carbonate ions (E 1–3). This dissolved inorganic carbon in waters of soils, rivers, oceans and the earth's crust, is stored for periods up to thousands to millions of years.

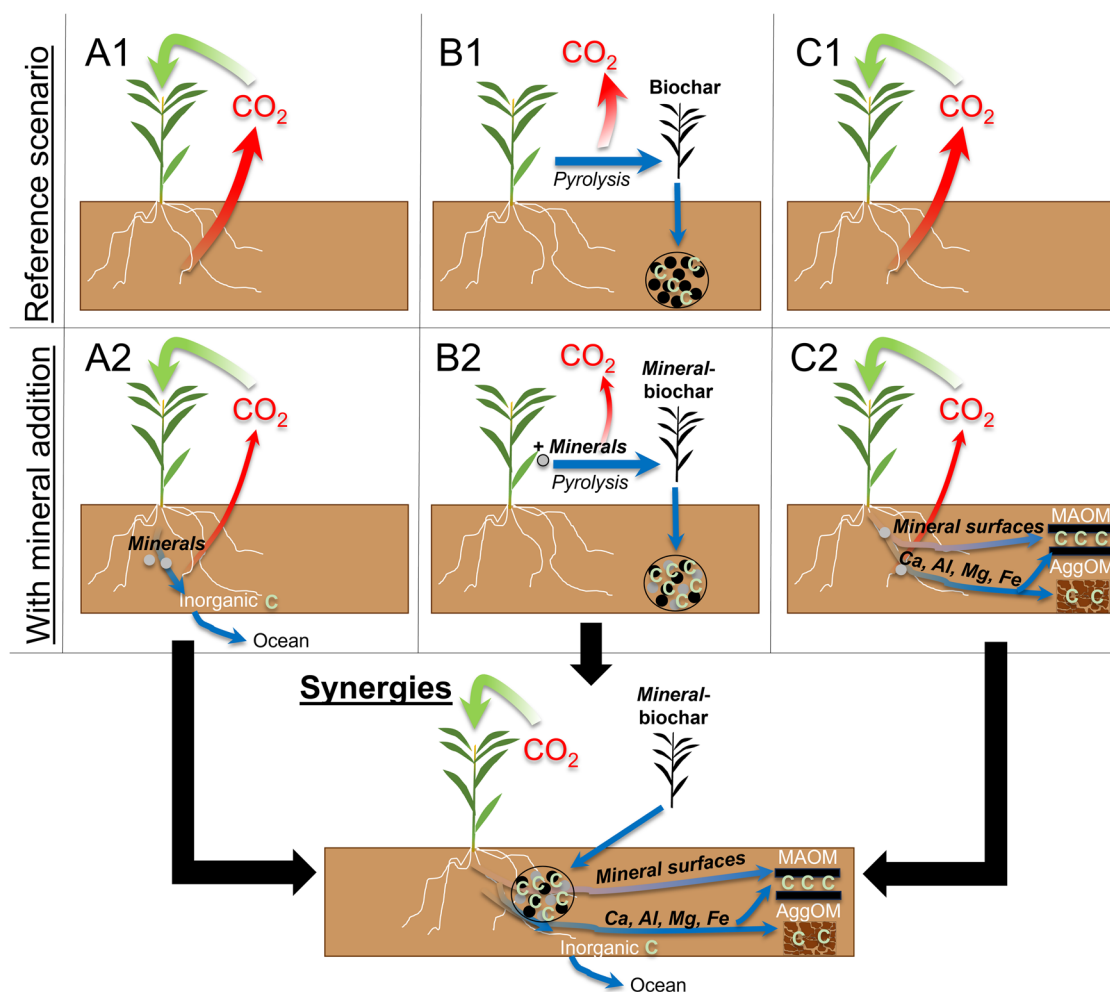
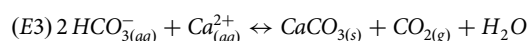
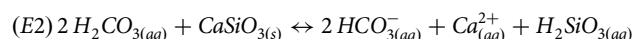
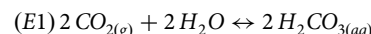


Fig. 1 | Role of minerals in three soil-based carbon dioxide removal methods. **A** Enhancing carbon retention as inorganic carbon through enhanced rock weathering, **B** enhancing stable biochar formation via pyrolysis facilitated by addition of minerals, and **C** limiting respiratory CO₂ emission by enhanced conversion of plant carbon into persistent soil organic carbon (matter). In panels under 1 (top) the

reference scenario is outlined and in panels under 2 (middle) the effect of minerals on these reference scenarios are shown. In the bottom panel, we highlight synergies between the three methods. MAOM stands for mineral-associated organic matter, and AggOM for aggregated organic matter.

Weathering processes can be enhanced by crushing rock particles to increase the rock surface area and accelerate the rate of chemical weathering, thereby sequestering substantial CO_2 amounts on societally relevant timescales^{25,27,28}. In practice, this CDR method involves the crushing of Ca- and Mg-rich silicate rocks, followed by their application in an environment suitable for weathering, such as agricultural soils, oceans, or more controlled closed pits or reactors¹⁵. An emerging body of literature has focused on EW in croplands, where the biological activity of soils and plants may accelerate the rate of weathering (e.g., as through the release of organic acids)²⁹ and potentially provide other co-benefits, such as enhanced crop yields and soil nutrients^{24,30,31}.

The reactivity and hence weathering rate of different silicate rock minerals is shown by the Goldich dissolution series²⁷, which is based on mineral formation conditions (cooling temperature and pressure) and associated crystallisation (Bowen's reaction series). Ultramafic rocks (richest in Ca and Mg) weather most rapidly but often contain elevated levels of Ni and Cr, which are potentially toxic to plants and humans^{17,32}. Hence, application of mafic rocks, such as basalt, has gained particular attention due to their natural abundance, typically low levels of toxic elements^{24,33}, and repeatedly demonstrated capacity to provide nutrients to plants and mitigate soil acidity^{17,24,34}.

For applicability of EW as CDR method, greenhouse gas emissions associated with rock mining, grinding and transport need to be outweighed by CDR from Ca and Mg silicate reaction with CO_2 (Fig. 2.1). Such emissions are calculated in life cycle GHG emission assessments, which show an overall net removal in various studies^{15,31,35}. Based on the rock mineral composition, theoretical CDR from reaction of minerals with carbonic acid (and, thus the carbon dioxide bound within) can be calculated^{27,36}. However, one key limitation for the use of EW as a CDR method is uncertainty in the rate of weathering in natural systems and the amount of net CO_2 removed due to complex reactions within soil and further downstream. These uncertainties arise from challenges associated with tracking carbon from the site of weathering (i.e. surface soil) to the ultimate site of sequestration (i.e., the deep ocean), inconsistent measurement approaches^{37,38}, and substantial natural variability with weathering rates impacted by a range of factors including water availability, soil chemistry, biological activity, and temperature.

To assess EW-associated CDR, the weathering products, Ca/Mg and bicarbonate/carbonate, are typically measured within soil leachate. Difficulties arise, however, due to soil's cation exchange capacity that can delay the leaching of EW products and their durable sequestration from years to decades^{39,40}. EW products can also be measured in soil, yet this relies on isolation of the weathering signal from the significant background effects from rock and soil cations and carbonates^{39,40}. Further complications are associated with non-carbonic acid weathering of silicate minerals producing Ca and Mg without bicarbonate, secondary reactions of Ca and Mg (e.g., carbonate formation) and outgassing of CO_2 within the soil column and through riverways to the ocean that reduce CDR efficiency^{40,41}. Ultimately,

while our understanding of the complex soil processes and spatiotemporal delays in EW CDR are still developing, the most effective approach to EW measurement is likely to be maximising sampling and measurement, including of the soil fraction (assessing precipitated carbonates, exchangeable cations and net cation loss), the leachate fraction (assessing alkalinity, inorganic carbon, cations and anions) and perhaps even the gaseous fraction (e.g., assessing CO_2 in- and out-gassing through flux chambers)⁴². There are also key unknowns for how EW will interact with SOM cycling in soils (discussed further below in Section 3.1).

The uncertainty in the rate of net CO_2 removal, beyond natural processes, leads to measurement and modelling variability and uncertainty in the cost per tonne of CO_2 sequestered. In general, application rates of silicate rock-based soil amendments are in the range of 10–220 t ha⁻¹ (typically 10–50 t ha⁻¹), which is very high relative to application rates of other agricultural soil amendments, such as lime (<5 t ha⁻¹)³⁰. The mining, grinding, transport, and distribution of rocks at such high volumes may limit the scalability of EW, as do discussed challenges around measurement, reporting and verification⁴³. However, at a fundamental level, EW appears to be a promising approach as CO_2 is sequestered on effectively permanent timescales, and there may be concomitant benefits to soil health and crop productivity²⁴.

Mineral-enriched biochar from biomass

Biochar is produced via pyrolysis, the heating of biomass at temperatures between 350 and 750°C in the absence of oxygen. This process stabilises on average just over half of the carbon within biomass (across different pyrolysis temperatures)⁴⁴, which subsequently persists in the environment for decades to millennia⁴⁵. However, on average ~45% of the carbon within biomass is lost during pyrolysis and not all carbon within biochar is stable on such time scales; a small proportion (3%) decomposes relatively rapidly⁴⁶. The amount of net sequestered carbon per tonne of biochar spread on land depends on GHG emissions associated with feedstock acquisition, biochar production, transport and spreading, and biochar carbon content and stability^{7,47} (Fig. 2.2, 2.3).

Biochar properties, including its carbon content and stability, are governed by pyrolysis temperature and biomass feedstock with some, but smaller, effects of particle heating rate and residence time at the highest treatment temperature^{48,49}. The biochar yield decreases with pyrolysis temperature while the carbon stability within biochar increases. Across both these effects, pyrolysis temperature only has a marginal influence on biochar stable carbon yield^{48,50,51}. Mineral doping, however, appears to have a notable effect on biochar stable carbon yield, especially in the temperature range 500–700 °C^{52,53}, while pyrolysis temperature in turn affects mineral stability and associated chemical reactions (see Buss et al.⁷).

The distribution of organic matter (and thus, carbon) and minerals (ash) in biomass feedstock also influences biochar's carbon sequestration potential⁷. While a higher carbon content proportion allows for more sequestered carbon per tonne of biochar produced, minerals can also

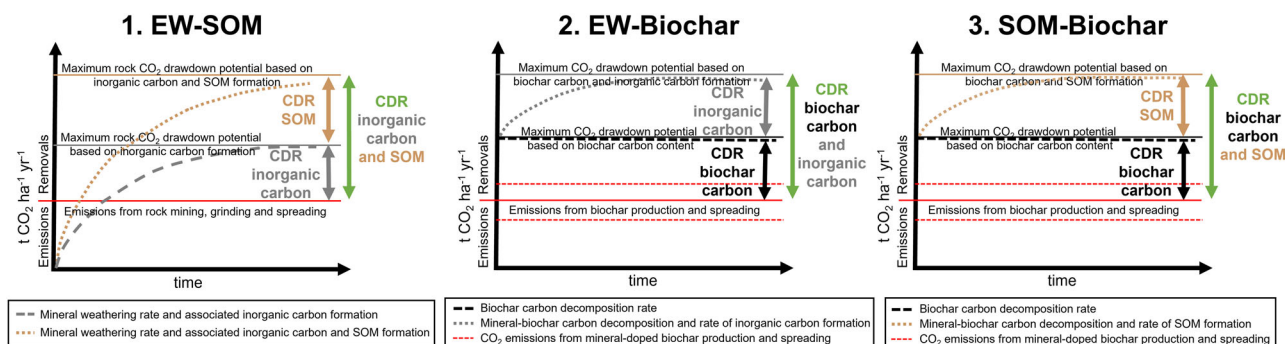


Fig. 2 | CO_2 emissions and removals associated with mineral-based carbon dioxide removal (CDR) methods applied to soils and their synergies. (1) Addition of minerals to soil for enhanced weathering (EW) and soil organic matter (SOM)

formation, (2) biochar/mineral-biochar production and addition to soil for inorganic carbon formation through enhanced weathering, (3) biochar/mineral-biochar production and addition to soil for soil organic matter formation.

increase biochar's CDR potential per tonne of biomass feedstock. The latter operates through two mechanisms: catalytic reactions and physical protection of carbon release. First, minerals present within biomass increase biochar carbon retention and stability through catalytic effects that reduce the activation energy for biomass conversion processes^{54,55}. Such minerals can also be added externally during pyrolysis to increase carbon retention and increase biochar stable carbon yield⁷. Different minerals are suitable for this effect, including K-, Na-, Ca-, Mg-, P- and Fe-containing minerals, and can be added in refined and unrefined form and residues⁷. To be cost-effective and enable large-scale use, unrefined minerals are preferred⁷. Second, minerals can act as physical barriers during biochar production, reducing carbon losses due to suppressed release of organic molecules^{52,56,57}. This is mainly attributed to oxides and carbonates of Ca and Mg formed during biochar production, but also P and Si that crosslink with the main carbon framework and thus reduce the release of small carbon compounds⁵⁷. These processes are different to the catalytic biochar formation described before, and protect the carbon both during pyrolysis, and after application to soil.

Minerals can be added to biomass dissolved in water⁵³ or in solid form, mixed with biomass and subsequently pelletised, although this adds further costs to the process⁵⁸. Mineral addition to biomass prior to biochar production is economically viable if the savings due to increased carbon conversion efficiency (and associated lower feedstock requirements to produce the same amount of stable carbon) outweigh the costs of mineral procurement, potential pelletisation, biochar production and application⁷. The added non-carbon (mineral) material increases pyrolysis unit running times and biochar application mass to produce and spread the same amount of stable carbon. However, with lower production costs due to economy of scale (lower costs for biochar production units), the method should become more economically viable over time⁷.

Mineral addition to soils to boost SOM accrual and stabilisation

While a portion of organic carbon in soil cycles quickly (minutes to years), another portion cycles much more slowly – with turnover times of decades to millennia⁵⁹. For organic carbon to persist over long time scales in soil, there must be physical and/or chemical mechanisms that limit microbial access to this carbon (excluding pyrolytic carbon)²². Such protection can occur by physical separation from microbial decomposers in soil aggregates (AggOM), or through physical and chemical association with the soil mineral matrix (known as mineral-associated organic matter; MAOM)⁶⁰. On average, MAOM is the slowest-cycling SOM fraction, and it forms when organic matter is in association with reactive secondary minerals in soil. These reactive secondary minerals are one of the products of weathering of primary minerals (such as contained in basalt rock). Over long-time scales, rock weathering leads to accrual of MAOM in soils⁶¹.

There is overlap in the processes that hold organic matter and minerals together in both MAOM and AggOM⁶². Aggregate formation involves flocculation of negatively charged soil particles by diverse cations (Fe, Al, Ca and Mg) that form positively charged bridges between negatively charged soil surfaces (polyvalent cation bridging). Aggregates can also be formed by cementation of soil particles facilitated by crystallised minerals, such as Fe oxides and carbonates and poorly crystallised minerals^{62,63}. During MAOM formation, primarily negatively charged soil minerals interact with mainly negatively charged organic matter to form bonds of different strengths^{62,64} through weaker adsorption reactions and more stable coprecipitation reactions⁶⁴. Besides providing negatively charged surfaces for MAOM formation, minerals release cations that link negatively charged surfaces with negatively charged SOM (polyvalent cation bridging)⁶². Therefore, the specific mineralogy and the quantity of soil exchangeable cations together determine SOM content; i.e., soil exchangeable Ca correlates well with SOM content in alkaline soils, while Fe and Al-oxyhydroxide contents correlate well in acidic soils^{61,62,65,66}.

Strategic amendments of reactive secondary minerals (such as allophane or iron oxides) may increase the SOM storage capacity of soil by

enhancing the MAOM and AggOM pools²³. Such application of small mineral quantities to plant root zones can effectively improve stabilisation of plant exudates⁶⁷. For such a method to be environmentally and economically sustainable, it needs to be reliable and predictable, yet there is little to no research in this area to date. Given the large interest in SOM accrual in agricultural areas for both agronomy and environmental (including climate) benefits, and a large body of research into mineral involvement in SOM storage^{64,66}, there is considerable potential for expanding research into soil amendment with selected minerals for SOM increase⁶⁸. Such research should focus on degraded and highly-weathered soils, which are limited in their ability to retain plant carbon due to low exchangeable cation concentrations and few ion exchange sites⁶¹. These soils may benefit most from mineral amendments for extra SOM accrual⁶¹.

Synergies between methods to enhance CDR

While these three soil-based CDR methods that use minerals (EW, biochar, SOM accrual) have traditionally been viewed in isolation from one another, there is clear scope for synergies between them. That is, strategic deployments of mineral amendments have the potential to sequester carbon through more than one CDR method; e.g., by directly sequestering inorganic carbon through EW, increasing the carbon sequestration efficiency of biochar, and by enhancing the capacity of soil to store organic carbon as MAOM and AggOM (Fig. 1). Allowing for both inorganic carbon and SOM formation in soil does not require any additional preparation, only rock mining, grinding and spreading. Therefore, no extra costs are associated with simultaneous inorganic carbon and SOM formation (Fig. 2.1); yet any increase in the CDR impact directly reduces the costs per CDR unit, which makes this an economically attractive strategy. The costs for producing mineral-biochars can be higher than the costs for producing biochars not doped with minerals. However, doping can also reduce biochar CDR costs due to a lower requirement for biomass feedstock to produce the same amount of stable carbon (further discussed in section 2B and Buss et al.⁷) (Fig. 2.2, 2.3). Inorganic carbon and SOM formation adds extra CDR on top of CDR associated with the carbon content within biochar (Fig. 2.2, 2.3). This section discusses how such synergies between the CDR methods can be achieved, specifically examining optimal mineral type and environmental/climate properties.

EW - SOM synergies

Finely ground Ca- and Mg-rich silicate rocks that remove atmospheric CO₂ during weathering and store it in inorganic forms, can also help form MAOM through the release of reactive secondary minerals that bind SOM, and promote retention of SOM in aggregates through mechanisms like cation bridging. Although limited research exists in this area, the interaction between these processes has been posited in various studies^{61,69}, and the concept was directly tested in a laboratory study using a blend of basalt and granite⁶⁸ as well as recent field studies applying meta-basalt in the Central Valley of California, USA⁷⁰ and wollastonite in a forest in the southeast of China⁷¹. At the same time, negative interactions can occur between EW and SOM cycling, such as when SOM loss is stimulated by pH increases associated with rock amendments. These pH increases (or other mechanisms) can lead to increased microbial priming of SOM⁷² and SOM loss⁷³ or may simply reduce accrual rates of MAOM over time. As there is very limited field data to date, it is critical for the interactions between EW and SOM cycling to be better studied and characterized, especially across different environmental contexts (soil and plant type, climate) and multi-year timescales.

Plant productivity is positively associated with SOM accrual, since greater productivity is typically associated with greater plant carbon inputs into the mineral soil, which can then form SOM⁷⁴. Therefore, carbon removal via EW and SOM accrual may be best suited for climates with high net primary productivity and fast rates of weathering (e.g. acid soils in tropical regions). Biological activity accelerates rock weathering through various mechanisms, such as the exudation of organic acids that increase

mineral dissolution, and through plant uptake of weathered ions that disrupt the dissolution equilibrium and thus allow for more rock dissolution^{34,75}. Microbes are also intimately involved in the formation of MAOM, as they process plant carbon into simpler biomolecules that form MAOM, and because microbial necromass (dead microbial bodies) is a key constituent of MAOM^{76,77}. Greater microbial growth and activity thus are often associated with greater MAOM accrual^{78,79}. Hence, greater microbial activity should help accelerate both rock weathering and MAOM accrual rates. New research is needed to advance understanding of how different primary and secondary mineral amendments may be added together to optimise rates of rock weathering and MAOM accrual rates, and how biological activity may be harnessed to maximize organic and inorganic carbon drawdown rates.

EW - biochar synergies

Mineral doping, i.e., mineral addition to plant biomass, can lead to higher carbon content and stability of the subsequent biochar, after pyrolysis. The added minerals could also help draw down carbon via EW, if they have significant Ca and Mg silicate or oxide contents. Fast-weathering minerals that are used for EW comprise easily soluble (reactive) Ca and Mg that interact readily with carbon during pyrolysis. Using such minerals can protect carbon both during pyrolysis and after biochar soil application⁵⁷. No research exists in this area so far that would enable quantification of such effects.

High soil water availability and biological activity promote high rates of rock weathering, but also increase biochar decomposition rate⁴⁶. However, weathering rates are several times higher in wet and warm climates than in arid environments^{80,81}, while biochar decomposition is increased by only 20–30%^{82,83}. Thus, application in wet and warm conditions should still lead to increased net carbon accrual. Areas with high soil moisture availability and biological activity should be suitable environments for co-application of rock amendments and biochar (or biochar doped with rock powder prior to pyrolysis). Co-application of rock amendments and mineral-enriched biochar should also enhance soil nutrients, increase pH, and benefit water and nutrient retention⁷.

SOM - biochar synergies

Among the interactions between the three CDR methods discussed above, reduced SOM decomposition and increased SOM accrual in response to biochar application to soils has been investigated in the most detail⁴⁵. This process has been shown to have greater potential to build SOM than cover crop use, stubble retention, or other climate-smart agricultural practices^{84,85}. In agriculturally productive soils in Iowa (US), for example, biochar addition sequestered as much additional SOM as was added with the biochar itself⁸⁶. On average, the SOM accrual effect induced by biochar addition amounted to 0.5–1.2 t C ha⁻¹ yr⁻¹, yielding a total mean SOM increase of 13 t ha⁻¹ in field trials that lasted 1–10 years^{18,87}. While biochar application initially may promote some SOM decomposition due to the labile carbon component in biochar, this initial extra SOM decomposition is outweighed over time by extra SOM accrual⁴⁵.

A key mechanism responsible for biochar SOM accrual is sorption of organic matter onto biochar that increases the upper limit of SOM storage^{18,88}. So far, this SOM accumulation has been attributed mainly to biochar's high surface area and carbon content, which provide new active surface sites for SOM accrual^{18,89}. However, interactions between biochar and soil minerals also mediate this process⁹⁰. Therefore, it is likely that strategic doping of biochar with minerals with a high sorption capacity, such as goethite, could accelerate this effect and boost the biochar effect on SOM accrual. We are not aware of any studies that have attempted to optimise biochar for this effect. We suggest that the same minerals responsible for natural SOM accrual in soils (Table 1) would likely also increase biochar-based SOM accrual if biomass is doped with such minerals prior to pyrolysis. The environmental factors that could maximise synergies include soils with low SOM sorption capacities and systems with high plant carbon input.

Mineral suitability for synergies between CDR methods

In this section, we discuss a range of minerals in detail with respect to their suitability for mineral-based CDR approaches, including global availability and cost, which are prerequisites for large-scale application of mineral-based CDR. Table 1 shows a detailed evaluation of mineral suitability for the three main CDR methods, and Fig. 3 summarises key results for different mineral classes.

Primary silicates

Primary minerals formed by magma crystallisation can vary from unreactive and nearly inert minerals (quartz) to highly reactive minerals (olivine, wollastonite). Depending on their mineralogy, primary minerals can be suitable for all three CDR methods. Highly reactive primary minerals facilitate: (i) rapid weathering that could sequester carbon as inorganic carbon when Ca- and Mg-silicates are present, (ii) cation release (mainly Ca, Mg, Fe and Al) that can facilitate soil aggregation and organic matter sorption to minerals (e.g., polyvalent cation bridging for MAOM formation and aggregation processes⁶⁶), (iii) potential formation of secondary minerals capable of forming MAOM, and (iv) catalysis/carbon protection during pyrolysis. However, increased SOM mineralization has also been observed after primary silicate (wollastonite) addition to soils, due to a soil pH increase from the acidic to neutral range, which increased microbial metabolism⁷². Furthermore, fast-weathering Fe-rich minerals, such as fayalite, are not suitable for inorganic carbon formation since secondary reactions in an oxic environment form and precipitate Fe hydroxide⁹¹. This is an acid producing reaction since OH⁻ is incorporated into the precipitate, which counteracts the CO₂ consumption of the initial reaction⁹¹.

Olivine (nesosilicates, orthosilicates) can catalyse biochar formation⁹², and Mg-rich olivine (forsterite) has very high potential for EW and associated inorganic carbon formation (Table 1). However, olivine can be contaminated with Cr and Ni, both of which are potentially toxic to plants, limiting the use of olivine in soils¹⁷. Globally, olivine is mined in quantities of ~9,000,000 tonnes annually at costs of around \$18–90 per tonne⁷. Wollastonite (inosilicate-single chain; CaSiO₃; present in metamorphic rock) can weather quickly and has strong potential for inorganic carbon formation^{27,93} (Table 1), though it is expensive (300 US\$ t⁻¹)⁷ and may not be economically viable in a pure form. Serpentine is a Mg-Fe-phyllosilicate that derives from metamorphosed ultramafic rock. It typically has a >10-time slower weathering rate than olivine, yet treatment at 600–700 °C increases the weathering rate substantially to values higher than those of olivine^{94,95}. The efficiency of serpentine conversion into its reactive form is enhanced in the presence of an inert atmosphere (i.e., absence of oxygen), as is also required for biochar production⁹⁶. Therefore, biomass feedstock doping with serpentine could bring synergies for biochar production (catalysis) as well as subsequent EW of serpentine in soils. The micas biotite, phlogopite, and muscovite (phyllosilicate) have medium weathering rates according to the Goldich dissolution series²⁷, low Ca and Mg silicate contents and little functionality (exchange capacity) for SOM accrual, but may have some potential for catalysing biomass pyrolysis⁷ (Table 1). Also, weathering rates (in the form of K-release) were found to increase after thermal treatment⁹⁷. Micaceous minerals are mined with an annual production of only 287,000 tonnes globally at a price of 121 US\$ t⁻¹¹⁷. Structurally stable alkali feldspars (e.g., orthoclase), a major part of igneous rocks, are typically poorly reactive and do not contain Ca and Mg²⁷. Therefore, they are unsuitable for inorganic carbon formation through EW and have little effect on biomass pyrolysis⁹⁸ or abiotic SOM sorption⁹⁹. Thermal treatment could increase feldspar reactivity for biochar catalysis¹⁰⁰.

To enable large-scale application of primary minerals for carbon drawdown, rock processing must be minimised to reduce economic costs and associated CO₂ emissions¹⁵. In the natural environment, minerals exist as rocks with complex compositions. Basalt is a Ca- and Mg-rich, mafic, igneous rock that contains minerals, such as olivine, micas, plagioclase feldspars and alkali feldspars. In a recent study, 50 t ha⁻¹ of partially weathered basalt and granite mining residues were applied to a

Table 1 | Assessment of mineral/rock/residue types regarding their suitability for (enhanced) inorganic, soil organic and biochar carbon formation

Mineral type/mineral	Ca-Mg silicate and oxide contents ^a	Weathering rate ^b	Exchange capacity ^c	(Predicted) potential for (enhancing) CDR		
				Inorganic carbon ^d	Facilitating SOM ^e	Biochar carbon ^f
Primary silicates						
Forsterite (Mg-rich olivine)	Very high (5)	Very high (5)	Very low (1)	Very high (5)	Medium (3)	Medium (3) ⁹²
Fayalite (Fe-rich olivine)	None (0)	Very high (5)	Very low (1)	None (0)	Medium (3)	Medium (3) ⁹²
Wollastonite	Very high (5)	Very high (5)	Very low (1)	Very high (5)	Medium (3)	(Medium (3))
Serpentine	Very high (5)	Very high (5)	Very low (1)	Very high (5)	Medium (3)	(Medium (3))
Ca-plagioclase feldspar	Very high (5)	High (4)	Very low (1)	Very high (4.5)	Medium (2.5)	(Low (2))
Pyroxene	Variable (2–4)	High (4)	Very low (1)	High (3–4)	Medium (2.5)	(Low (2))
Micas (biotite)	Low (2) ²⁷	Medium (3)	Very low (1)	Medium (2.5)	Low (2)	(Low (2))
Alkali feldspar	Low (2)	Low (2)	Very low (1)	Low (2)	Low (1.5)	Low (2) ⁹⁸
Quartz	Low (2)	Very low (1)	None (0)	Very low (1)	None (0)	Very low (1)
Primary silicates-containing rocks						
Basalt	High (4)	High (4)	Very low (1)	High (4)	Medium (2.5)	(Low (2))
Secondary phyllosilicate						
Illite	Low (2) ¹³¹	Low (2)	High (4)	Low (2)	Medium (3)	High (4)
Smectite (montmorillonite)	Low (2) ¹³¹	Low (2)	High (4)	Low (2)	Medium (3)	High (4) ¹⁰¹
Vermiculite	Medium (3) ¹³¹	Low (2)	High (4)	Medium (2.5)	Medium (3)	High (4) ⁵²
Kaolinite	Very low (1) ¹³¹	Low (2)	Medium (3)	Low (1.5)	Medium (2.5)	Medium (3) ^{103,104}
Ordered Fe and Al oxides						
Lepidocrocite	None (0)	High (4)	High (4)	None (0)	High (4)	NA
Goethite	None (0)	High (4)	High (4)	None (0)	High (4)	Negative effect (–1) ¹⁰⁹
Hematite	None (0)	High (4)	High (4)	None (0)	High (4)	NA ^{101,109}
Gibbsite	None (0)	High (4)	High (4)	None (0)	High (4)	NA
Short-range ordered aluminosilicates						
Allophane	None (0)	Very high (5)	Very high (5)	None (0)	Very high (5)	NA
Imogolite	None (0)	Very high (5)	Very high (5)	None (0)	Very high (5)	NA
Non-crystalline gibbsite	None (0)	Very high (5)	Very high (5)	None (0)	Very high (5)	NA
Ferrihydrite	None (0)	Very high (5)	Very high (5)	None (0)	Very high (5)	NA
Nano-crystalline goethite	None (0)	Very high (5)	Very high (5)	None (0)	Very high (5)	NA
Non silicates and residues						
Iron-ore tailings	Variable (2–4)	High (4)	Low (2)	High (3–4)	Medium (3)	Very low (1) ¹⁰⁹
Lime, calcite, gypsum	Very low (1)	High (4)	Low (2)	Medium (2.5)	Medium (3)	NA
Combustion ashes	High (4)	High (4)	Low (2)	High (4)	Medium (3)	High (4) ⁵⁸

Evaluation on a score from 0 (not suitable/none) to 5 (very high).

NA not available; no literature data, cannot be predicted based on current literature or contradicting literature data.

^aBased on chemical formula or literature reference.

^bBased on Palendri et al.¹³² or mineral of comparable structure.

^cMainly based on Singh et al.⁶⁶.

^dMean of score for Ca/Mg content and weathering rate (if either of the parameters was scored zero, an overall score of zero was given).

^eMean of score for weathering rate reflecting cation release (AggOM formation) and secondary mineral formation (MAOM formation) and exchange capacity reflecting ability to directly sorb organic matter without weathering (if either of the parameters was scored zero, an overall zero was given).

^fBased on literature or when in brackets predicted based on properties comparable to minerals tested in the literature.

sandy soil, which reduced SOM losses by up to 32%⁶⁸. This effect was related partly to the formation of MAOM and AggOM, as a result of readily available Ca and Mg. Calcium carbonate that can precipitate in soils during weathering of Ca- and Mg-rich silicate rocks plays an important role in SOM stabilisation in aggregates. Another benefit of using mining residues as a source of rock dust is economic viability (>4 billion tonnes of crushed rock is mined globally, at values of ~12 US\$ t^{–1} ref. 7), yet this area remains poorly explored.

Secondary phyllosilicates (clay minerals)

Secondary phyllosilicates form in soil through weathering of primary silicate minerals. Despite some (low) levels of Ca and Mg silicates (Table 1), such secondary (clay) minerals have low capacity for further weathering and, hence, are not expected to drawdown significant amounts of carbon through inorganic carbon formation (Table 1). However, they have a high surface area with (predominantly negative) charges that associates with SOM, and could also be suitable for doping biomass prior to pyrolysis.

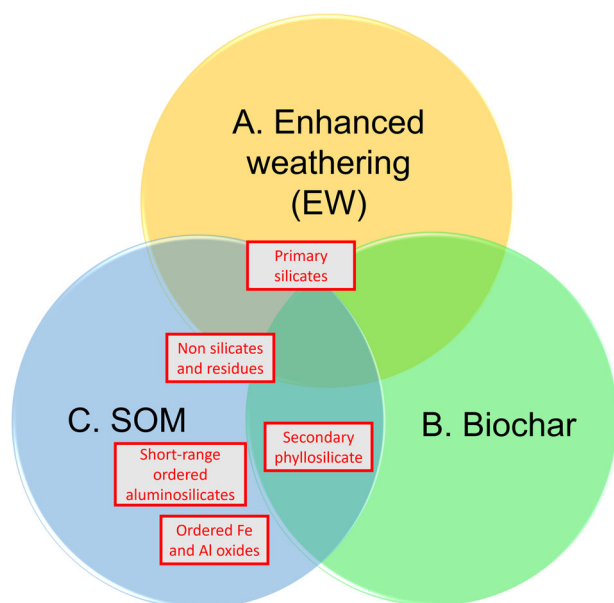


Fig. 3 | Potential of mineral classes to result in carbon dioxide removal synergies.

A Enhanced weathering (EW), **B** biochar production and utilisation and **C** soil organic matter (SOM) accrual. Relative positioning of mineral classes (red squares) demonstrates their suitability for use for respective carbon dioxide removal method, including potential synergies when located at the overlap of two or even three circles, i.e., secondary silicates are suitable for soil organic matter and biochar, while primary silicates mainly for enhanced weathering with some potential for both other methods (based on assessment in Table 1).

To enable efficient MAOM formation, minerals need to have a large surface area and surface charge, which is the case for the three-layer illite, smectites (e.g., montmorillonite), and vermiculite clay minerals that have a high capacity to protect SOM and facilitate its accrual⁶⁴ (Table 1). Conversely, the two-layer clay mineral kaolinite has lower capacity to protect SOM⁶⁶. While organic matter sorption to different phyllosilicates has been relatively well investigated, only some minerals have been tested for biomass doping to increase biochar yield and stability. Thus far, promising results have been observed primarily with minerals with high reactivity in soils, such as vermiculite and montmorillonite (and bentonite)^{52,101}. Vermiculite, for example, has a K content of 0–1.7%¹⁰² that could catalyse biochar formation and a Ca and Mg content of 12–18%¹⁰² that could protect and hence retain carbon during pyrolysis. Addition to straw prior to pyrolysis increased both carbon retention and stability with largest effects observed in the temperature range 600–700 °C⁵². The effects of kaolinite on biochar carbon yield and stability are less certain with both no effect¹⁰³ and positive effects observed¹⁰⁴.

Some clay minerals are commercially mined and may be suitable for large scale application, such as bentonite that comprises mainly smectite minerals with global production rates of 20,900,000 t per year at 98 US\$ t⁻¹, or vermiculite with global production rates of ~533,000 t per year at 140 US\$ t⁻¹ ref. 7.

Ordered Fe and Al oxides and short-range ordered aluminosilicates

Oxides and (oxy) hydroxides of Al and Fe (sesquioxide) and poorly crystalline Al and Fe phases (short-range ordered aluminosilicates) have a high capacity for SOM stabilisation. Due to their high surface area and reactivity, these minerals have greater capacity than phyllosilicate clay minerals for storing SOM^{61,65,105–108}. Therefore, such reactive secondary minerals could be ideal ingredients to enhance MAOM accrual. These minerals might also be suitable for biochar doping due to their reactivity, although negative effects on biochar carbon yield have been reported¹⁰⁹ and they have no potential for inorganic carbon formation since they don't contain Ca and Mg silicates and

oxides (Table 1). Due to their ability to bind large amounts of organic matter, these minerals can be applied in relatively small amounts, ideally focussed in the root zones of plants, to protect plant exudates.

Minerals with ordered structure, such as the Fe minerals lepidocrocite, goethite, hematite and magnetite, typically have a lower ability to protect SOM than poorly crystalline Fe minerals, yet are more stable¹¹⁰. Therefore, they may have a longer-lasting effect on SOM accrual than poorly crystalline minerals. Goethite, for example, has been successfully applied for extra SOM accrual in soils (notably, stabilisation of rhizodeposits) at an application rate of only 1.2 t ha⁻¹ ref. 67. Goethite and the Al oxide gibbsite can both sorb SOM and form stable aggregates by cementation of other minerals, fostering SOM protection⁶⁶. Biomass doping with two minerals – hematite and montmorillonite – increased biochar carbon stability¹⁰¹, whereas goethite facilitated thermal decomposition and hence carbon loss during pyrolysis, decreasing biochar yield^{109,111}. Given that Fe-ore that mainly consists of hematite and magnetite is already mined commercially on large scales (3,000,000,000 t per year), its apparent promise for CDR warrants urgent further study. However, given its current use, socio-economic assessments need to be conducted to evaluate the effect of competing Fe-ore uses and potential risks and benefits of opening new mines. In addition, Fe-ore mining waste and steel waste contain Fe and Ca oxides (1–40% Fe and 7–35% Ca), and show potential for CO₂ capture through EW^{112–114}. These widely available materials may increase SOM accrual¹¹⁰ but likely decrease stable biochar yield¹⁰⁹. Finally, we emphasize that future studies need to include consideration of the negative environmental implications of heavy metal contamination in iron ore, iron-ore waste, and steel slag.

Poorly-crystalline Al and Fe phases are primarily represented by short-range ordered aluminosilicates, which include the Al-minerals allophane (hollow sphere-shaped particles), imogolite (well-defined tube-shaped particles) and non-crystalline gibbsite, and Fe-minerals ferrihydrite and nano-crystalline goethite^{61,115}. These all have a high capacity for organic matter storage in soils, but data are lacking on their potential for biomass doping for biochar production, and for potential combined benefits on biochar and soil carbon stability.

Non-silicate rock minerals and residues

Soil exchangeable Ca correlates well with SOM⁶² and has been shown to be the best predictor of SOM in alkaline soils⁶⁵. Therefore, the addition of Ca-containing minerals to soils may increase SOM storage. Ca decreases respiration rates and increases SOM protection in MAOM and aggregates⁶². Lime, calcite, and gypsum application increases soil structure and hence the SOM protection potential⁶². Ca-bearing minerals in the form of liming agents have been applied for centuries, yet the effects of liming agents on SOM content are still not clearly understood. Negative, neutral, and positive effects have been reported, based on improved SOM decomposition due to pH increase, increased soil aggregation due to Ca supply, and better plant growth and hence more carbon inputs into soil, respectively^{116–118}. Overall, on average 4.5% SOM increase was reported in acidic soils as a result of liming agent addition¹¹⁹. Such application can be economical and sustainable given the expected increase in crop yield as a result of pH shifting in acidic soils into a range optimal for plant growth¹¹⁹. Specifically, Ca- and Mg-depleted soils could be suitable for amendment with Ca-containing minerals to facilitate SOM protection through AggOM and MAOM.

Biomass combustion ashes have complex chemical composition that mainly comprise metal oxides, with the largest proportion attributed to Ca, followed by K, Mg, Al, and Fe¹²⁰. Different studies of wood ash application to soils have shown a range of effects, from SOM loss^{121,122}, neutral effects on SOM¹²³, to even SOM accrual and decreased soil CO₂ emissions^{124–126}. This requires further investigation, with emphasis on soil chemical changes induced by wood ash in different soil types. Due to the presence of CaO and MgO, biomass combustion ashes can also result in the formation of carbonates in soils^{126,127}. Wood ash can also increase biochar stable carbon yield and biochar economics⁵⁸. Notably, biochar-wood ash composites can efficiently supply potassium to plants^{128,129}. Given the potential of wood ash to

offer a win-win-win scenario, it is a promising material for future studies. Although combustion ashes are not available in large quantities globally, they can become a locally important application where they are available, instead of going to landfill¹³⁰. It may offer an attractive application of combustion waste from biomass energy with carbon capture and storage (BECCS) installations if and when these become operational.

Conclusions

Here, we reviewed three soil-based CDR methods that use minerals, including (A) enhanced rock weathering for inorganic carbon formation, (B) mineral doping of biochar, for biomass carbon retention and (C) accrual of soil organic matter. We highlighted their potential use and limitations when applied individually for CDR. We then assessed the potential for synergies between inorganic carbon, soil organic carbon, and stable biochar carbon formation through strategic applications of primary and secondary minerals to soil, or as additive to biomass (biomass doping) before biochar production. We describe the suitability of a variety of minerals for these synergistic approaches and highlight how carbon can be drawn down simultaneously through multiple soil-based CDRs. We suggest that such synergies can reduce the economic costs of atmospheric CDR by concurrent draw down into organic carbon and inorganic carbon forms. The minerals with most potential for further investigations include primary minerals for SOM-EW synergies, phyllosilicates for SOM-biochar synergies, and combustion ashes for synergies across all CDR methods. Further research is urgently needed into optimising mineral formation through co-application of several minerals, i.e., primary and secondary minerals, to accelerate carbon draw down through several pathways. Optimisation of synergies between the CDR methods could boost CDR rates and increase economic feasibility, and hence favour large-scale rollout of land-based carbon sequestration.

Data availability

Table 1 represents all data used in this study.

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Author contributions

W.B. conceptualised the idea for the manuscript in collaboration with H.H. and N.W.S. W.B. prepared figures and wrote the manuscript. H.H., N.W.S., E.J.R., J.B. reviewed and edited the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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