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LETTER

Potential and costs of carbon dioxide removal by enhanced weathering of rocks

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Abstract

The chemical weathering of rocks currently absorbs about $1.1\,Gt\,CO_2\,a^{-1}$ being mainly stored as bicarbonate in the ocean. An enhancement of this slow natural process could remove substantial amounts of CO_2 from the atmosphere, aiming to offset some unavoidable anthropogenic emissions in order to comply with the Paris Agreement, while at the same time it may decrease ocean acidification. We provide the first comprehensive assessment of economic costs, energy requirements, technical parameterization, and global and regional carbon removal potential. The crucial parameters defining this potential are the grain size and weathering rates. The main uncertainties about the potential relate to weathering rates and rock mass that can be integrated into the soil. The discussed results do not specifically address the enhancement of weathering through microbial processes, feedback of geogenic nutrient release, and bioturbation. We do not only assess dunite rock, predominantly bearing olivine (in the form of forsterite) as the mineral that has been previously proposed to be best suited for carbon removal, but focus also on basaltic rock to minimize potential negative side effects. Our results show that enhanced weathering is an option for carbon dioxide removal that could be competitive already at 60 US $ t^{-1} CO_2 removed for dunite, but only at 200 US $ t^{-1} CO_2 removed for basalt. The potential carbon removal on cropland areas could be as large as $95\,Gt\,CO_2\,a^{-1}$ for dunite and $4.9\,Gt\,CO_2\,a^{-1}$ for basalt. The best suited locations are warm and humid areas, particularly in India, Brazil, South-East Asia and China, where almost 75% of the global potential can be realized. This work presents a techno-economic assessment framework, which also allows for the incorporation of further processes.

1. Introduction

In its fifth assessment report, the IPCC stated that scenarios consistent with a likely chance to keep temperature change below 2 °C relative to pre-industrial levels reach emissions levels near zero Gt CO_2eq or below in 2100 [1]. Consequently, the Paris Agreement calls for a balance between anthropogenic emission sources and sinks in the second half of this century. To achieve this goal, residual emissions of long-lived greenhouse gases, such as CO_2 emissions from transport and industry and N_2O emissions from agriculture, will have to be offset by carbon dioxide removal (CDR) technologies. In order to limit end-of-century warming to below 1.5 °C, offset of past emissions is likely going to be necessary [2]. A possibly important but yet to be better understood CDR option is the enhanced weathering (EW) of rocks [3].

Chemical rock weathering is an integral part of the global carbon cycle and removes about $1.1\,Gt\,CO_2\,a^{-1}$ from the atmosphere [4]. The natural weathering process can be enhanced by grinding selected rocks to small grain sizes to increase the specific surface area, and spreading them over forests and croplands in warm and humid regions [3, 5]. The rock material dissolves in the presence of water and CO_2 and dissolution

products are transported via rivers towards the ocean, where they are stored at millennial time scales [6]. If EW is deployed at a larger scale, it could potentially remove significant amounts of CO_2 from the atmosphere [3, 7].

Compared to other CDR technologies that require e.g. carbon capture and storage, the technical risks of EW are assumed to be rather low [8]. However, side effects and societal implications have to be considered. The literature so far has predominantly discussed dunite rock, which mainly bears fast-weathering forsteritic olivine. This mineral is best suited in terms of weathering efficiency, but unavoidably also carries harmful trace elements (specifically Ni and Cr), which can potentially be released into the environment during dissolution [9]. Only recently, basalt as an alternative rock source has gained more attention [5]. On average, it contains less harmful elements, and could even act as a fertilizer by providing elements that are in deficit in many tropical areas [10]. Basalt has a lower weathering efficiency, which could be partly compensated by increased plant biomass carbon, driven by nutrient release [11, 12].

Whether EW could be a relevant technology to mitigate climate change depends on two factors: its global annual CDR potential and its economic costs. To the authors' knowledge, only two previous studies have estimated the global potential of EW. One study is based on river catchments, indicating an upper limit for sustainable EW of about 3.7 Gt CO_2 a^{-1} (equivalent to less than 300 Gt CO_2 in the 21st century) for the humid tropics, governed by hydrochemical thresholds [13]. The second study [5] suggested very large potentials of up to 5500 Gt CO_2 removed from the atmosphere during the 21st century. These high potentials can only be reached when large areas of the tropics including forests are used. The difficult accessibility of tropical forests doubles the costs compared to cropland, thus reducing economic competitiveness.

In order to shed some light on a more competitive global deployment of the technology, we first show which weathering rates would have to be achieved to make EW a significant and cost-effective CDR option. The weathering rate depends on site-specific conditions and is subject to uncertainty. However, it can be enhanced by several orders of magnitude through grain size reduction. We show that costs of rock comminution are small compared to other cost components of EW, which turns it into an important lever to enhance the CDR potential of EW. It remains to be shown that the use of significantly reduced grain sizes would be scalable, as hydrologic properties would be changed and mixing into soils remains a critical unknown in the parameterization. Second, we assess the global annual CDR potential of EW based on global cropland, which can easily be reached by roads. Relying on the road network significantly reduces the costs and expands possible deployment areas beyond the tropics. Within a climate policy framework that aims

for emission neutrality, deployment of EW on cropland could provide one possibility to offset residual non-CO_2 emissions within the agricultural sector. Finally, we combine regional potential, expected weathering rates, and economic costs to provide a supply curve for EW. We consider both basalt and dunite rock in our study. Dunite rock has been thoroughly discussed in the literature and is therefore an important benchmark. Due to sustainability considerations, basalt is the more suitable material for deployment on cropland. In the future, however, mixtures of different rock types may be used to optimize the supply of beneficial geogenic nutrients for plants, or the potential to improve soil properties. As optimized rock products still need to be developed, the chosen rock classes remain the best candidates for the assessment.

Our study does not include the eventual biological storage of carbon in soils and plants due to mineral fertilization or other un-parameterized feedbacks, which may be particularly relevant for basalt. We also excluded potential hydrological effects, which may affect overall dissolution kinetics due to changes in hydrological flow path and residence time.
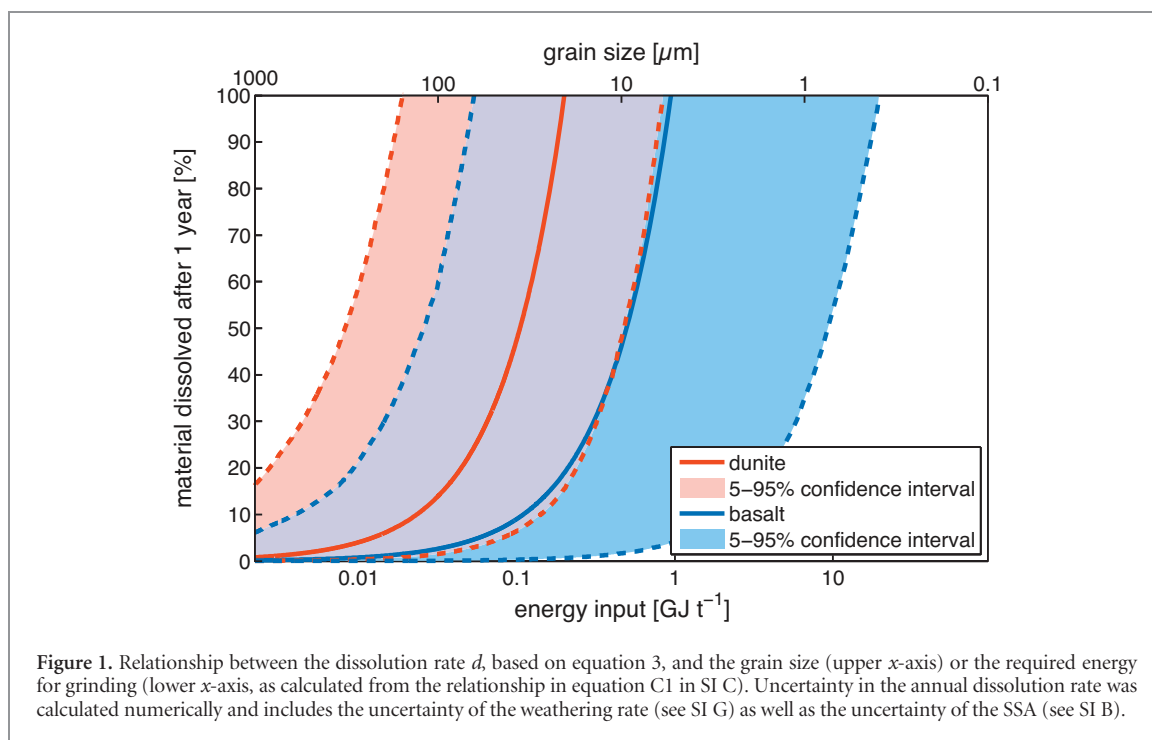
2. CDR rates

The annual CDR rate for a specific land area is the amount of CO_2 that can be removed from the atmosphere by EW. It determines the regional CDR potential. This rate depends on three factors: the amount of rock M spread on that area, the dissolution rate d, i.e. the share of rock that weathers every year, and the specific carbon sequestration potential P (CO_2 removal per ton of rock).

We assume an upper limit of $M = 15\,\mathrm{kg\,m^{-2}}$ ground rock that can in total be applied per area of land, with the annual application rate being generally much lower. This total amount is about equal to an 8 mm layer of rock powder, which is considered to be easily incorporated into soils by standard agro-technical machinery, e.g. a cultivator, and natural processes such as percolation and bioturbation ([5] and references therein).

The highest CO_2 sequestration potential (P) is expected from ultramafic rocks with low silica content like dunite, dominated by the mineral forsterite (Mg-rich olivine variety) with 1.1 t CO_2 per t dunite and mafic rocks such as the abundant basalt with 0.3 t CO_2 per t basalt (cf. SI A for details available at stacks.iop.org/ERL/13/034010/mmedia).

The dissolution rate is material specific and depends on the grain size x. In a steady state, where the rock mass spread on fields is sustained, the rock mass that weathers every year and will be replenished every year equals $d(x)\,M$. The annual amount of carbon removed $R_{co_2}(x)$ equals the weathered amount of rock in that year times the specific carbon sequestration potential P,

$$R_{co_2}(x) = m \cdot d(x) \cdot p. \tag{1}$$

Figure 1. Relationship between the dissolution rate *d*, based on equation 3, and the grain size (upper *x*-axis) or the required energy for grinding (lower *x*-axis, as calculated from the relationship in equation C1 in SI C). Uncertainty in the annual dissolution rate was calculated numerically and includes the uncertainty of the weathering rate (see SI G) as well as the uncertainty of the SSA (see SI B).

We use a catchment scale-based conversion to estimate the share of spread material that is dissolved within one year ($d(x)$), equation (1), figure 1) depending on the grain size *x*:

$$d(x) = \mathrm{SSA}(x) \cdot \mathrm{WR_{gain}} \cdot m \cdot t \qquad (2)$$

with SSA = specific surface area ($\mathrm{m^2\,g^{-1}}$, $69.18 * x$ $[\mu\mathrm{m}]^{-1.24}$, see SI B), $\mathrm{WR_{grain}}$ = grain surface area-based weathering rate ($\mathrm{mol\,m^{-2}\,s^{-1}}$), m = molar weight of dunite (considered to be 100% forsterite with $140.7\,\mathrm{g\,mol^{-1}}$) or basalt ($125\,\mathrm{g\,mol^{-1}}$; [23]), $t = 3.155 \times 10^7\,\mathrm{s\,a^{-1}}$ (to convert $\mathrm{WR_{grain}}$ from dissolution per second to dissolution per year).

Equation (2) represents an idealized dissolution process, neglecting grain surface changes during dissolution. Past studies have referred to an idealized general shrinking core model to derive relative dissolution [15, 16]. However, the model is based on perfect rather than highly irregular grains and is not able to convincingly reflect the observed specific surface area of natural mineral material, which can be up to 40 times higher (cf. SI B). The shortcomings of both models further corroborate the need for more specific studies. In addition, there may be grain size limitations on the lower end during field application regarding the transport of CO_2 towards the reactive mineral surfaces. Potential limitations need to be substantiated in laboratory and field studies.

The chemical weathering rate $\mathrm{WR_{grain}}$ of the material used is the key determinant for annual carbon removal rates. However, due to the manifold parameters that would have to be controlled, such as runoff, soil CO_2, root-soil interactions, etc, field-based weathering rates are only reported as bulk numbers, relating to the watershed surface area [17–19]. Since dissolution rates can be influenced by grain size reduction, grain surface-based weathering rates are needed here, which can hardly be derived from rates measured at the watershed scale [14]. We therefore rely on published rates from laboratories and models. However, they range over several orders of magnitude (e.g. [20]), which critically impacts the estimation of the global potential of CO_2 sequestration. Key controls are the temperature and the pH value. Temperature dependence is constrained by field observations via the Arrhenius reaction speed dependency (SI F), which leads to a difference in chemical weathering rates of a factor of three between warm and temperate regions. Fitted curve equations for the pH dependency were developed by Bandstra and Brantley [21], based on existing literature on lab-based weathering rates (SI G). Variations at constant T and pH can be explained by the experiment types used as well as the scale [22, 23], and basic analytical variations. These individual uncertainties are included in our analysis by adding upper and lower bounds defined by $\pm 1\sigma$ for the parameters of the curve fits in [21]. Biotic soil processes and high soil CO_2 concentration exert a strong influence on the weathering rate [24] but need to be better constrained and can only be discussed qualitatively. Taylor *et al* [5] have shown in an exemplary catchment where their model, which includes biotic processes, is able to reproduce rather fast lab-derived weathering rates [15, 22–25], whereas Brantley [16] calculated rates from an abiotic soil column experiment, that are at least two orders of magnitude lower. A larger experiment supports this finding for abiotic field weathering rates [26], which points towards a general underestimation if biotic processes such as soil respiration
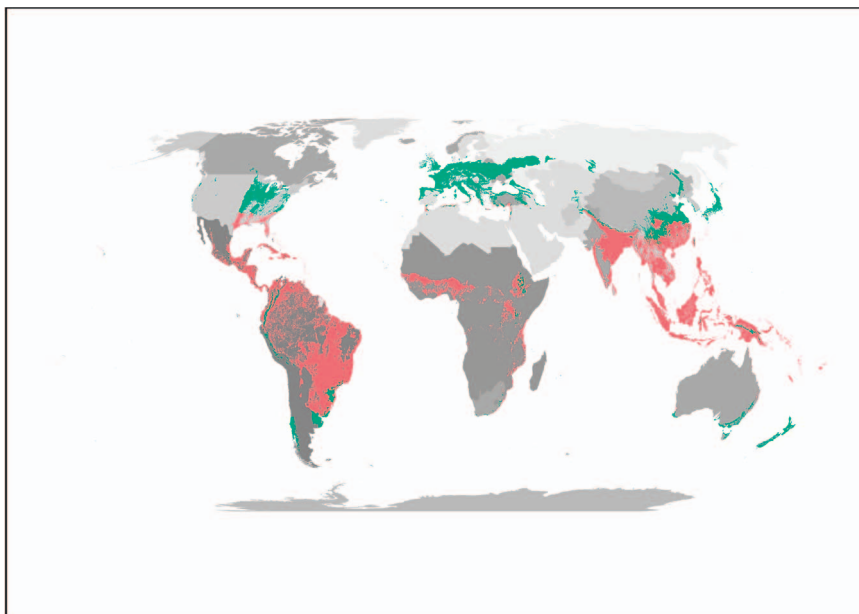
Figure 2. Global crop fields divided into warm (red areas) and temperate (green areas) humid climate, yielding two grades for the application of EW of rocks. Shaded areas represent the regional disaggregation. Representation of available cropland may appear more aggregated due to low figure resolution.

are disregarded. The manifold parameters involved introduce an uncertainty that has to be addressed in the future by means of field or plot scale studies. The rates used to calculate the weathering efficiency should therefore not be seen as an exact representation of the natural process. They rather provide a guideline in the sense that field-based rates, once they have been published, can be compared and evaluated for EW efficiency.

For basalt as a source material, grain scale weathering rate ranges are also widespread and in the same order of magnitude as dunite (e.g. [20]). The similarity of field weathering rates between basalt and dunite is backed by observations of comparable silicate weathering rates between volcanic and ophiolitic (forsterite-bearing peridotites, dunites, and gabbros) catchments [27]. In addition to the inclusion of plant-root-soil process parameters in global models [5], reliable field weathering rate measurements are needed to decrease uncertainties for CDR evaluations.

Therefore, a scalable relative model approach was chosen here, so that future data can be included for a technological evaluation update. This approach yields weathering rates of $10^{-10.53}$ $(10^{-12.63}-10^{-9.55})$ $\mathrm{mol\,m^{-2}\,s^{-1}}$ for basalt and $10^{-9.86}$ $(10^{-9.95}-10^{-9.77})$ $\mathrm{mol\,m^{-2}\,s^{-1}}$ for dunite, both for a pH of 7 and temperature of 25 °C (see SI G).

## 3. Regional and global CDR potential

Suitable deployment areas of EW need to fulfill two important requirements. As the chemical weathering reaction requires water, its general availability

throughout the year is an important precondition. Furthermore, the reaction is temperature dependent, being significantly faster under elevated temperatures (see SI F). Details on reactions and kinetics can be found in Hartmann *et al* [3]. Considering those two important base parameters, warm to temperate and humid regions are suitable deployment areas to ensure reasonably fast weathering rates.

While rock material can be applied on forests, pasture and on croplands, we restrict the analysis to the latter only because of practicality. Croplands are considered to have an existing infrastructure to make them easily accessible and agricultural machinery can also be used to spread rock powder. It can be assumed that water is provided either by rain or irrigation measures.

Potential application areas are therefore all croplands in sufficiently warm and humid areas (figure 2), which we divide into two grades, representing relative faster and slower weathering rates: warm and temperate. We calculate the standardized weathering rates based on the deviation of their respective average temperature from 25 °C using factors of 0.95 ± 0.20 for warm regions and 0.35 ± 0.22 for temperate regions (see SI F). Areas are derived from the global ecophysiography map by Sayre *et al* [28], considering bioclimatic and land use parameters (details on class selection in SI G). The overall suitable area of distinct geographic regions meeting minimum requirements of temperature and humidity is given in SI Table I-2. The total area identified as suitable is about 50% of the global cropland area [29].

Using equations (1) and (2) and the total global suitable area (5.1×10^6 km^2 in warm and 2.8×0^6 km^2 in temperate regions, see SI I-2), we can now calculate
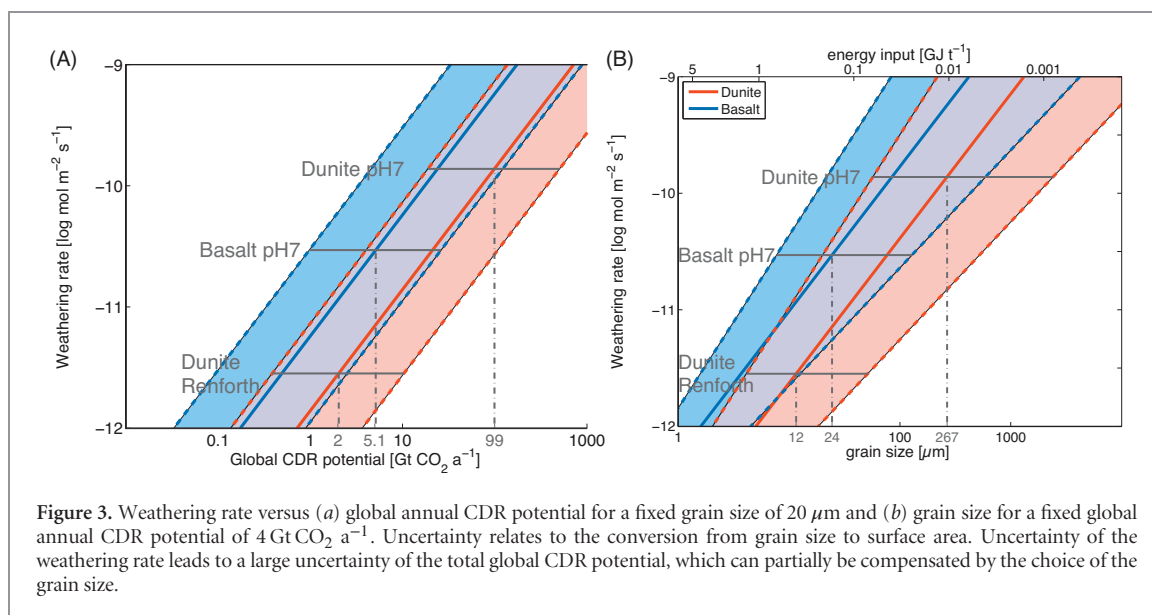
Figure 3. Weathering rate versus (*a*) global annual CDR potential for a fixed grain size of 20 μm and (*b*) grain size for a fixed global annual CDR potential of 4 Gt CO$_2$ a^{-1}. Uncertainty relates to the conversion from grain size to surface area. Uncertainty of the weathering rate leads to a large uncertainty of the total global CDR potential, which can partially be compensated by the choice of the grain size.

the global annual CDR potential in dependency of the grain size x and the weathering rate WR,

$$
\begin{aligned}
\mathrm{CRD}(x, \mathrm{WR}) &= A * R_{\mathrm{CO_2}}(x, \mathrm{WR}) \\
&= (A_{\mathrm{warm}} \cdot 0.95 + A_{\mathrm{temp}} \cdot 0.35) \\
&\quad \cdot M \cdot P \cdot \mathrm{SSA}(x) \cdot \mathrm{WR}_{\mathrm{grain}} \cdot m \cdot t.
\end{aligned} \tag{3}
$$

For a grain size of 20 μm, the weathering rates from section 2 yield a total global CDR potential of 4.9 Gt CO$_2$ a^{-1} and 95 Gt CO$_2$ a^{-1} for basalt and dunite, respectively (figure 3(*a*)). The weathering rates measured in [16] without plant and root activity would lead to a much smaller potential of 1.9 Gt CO$_2$ a^{-1} for dunite. The large spread of rates again demonstrates the need for further research that constrains the uncertainties of field weathering rates. For the same weathering rates, a grain size of 24 and 256 μm for basalt and dunite, respectively, would be needed to obtain a fixed global CDR potential of 4 Gt CO$_2$ a^{-1} (figure 3(*b*)). This amount of CDR would be sufficient to offset e.g. emissions from the industry sector in 2050 that remain despite an ambitious climate policy [30]. If the problem regarding possible health impact by very fine particles could be solved, e.g. by creating a slurry, even small weathering rates, such as reported by Renforth *et al* [16], could suffice to make EW a relevant CDR technology.

4. Techno-economic assessment

The main economic cost factors for EW are mining, crushing, and grinding of rocks, and transport to and distribution on crop fields. Only one of these factors, the cost for rock grinding, depends on the required grain size. The grain size is a crucial parameter for determining the annual CDR potential. A smaller target grain size increases the overall energy demand for the rock grinding (dependency shown in SI C) and thus costs. The production of ultrafine particles ($<10\,\mu$m)

is technically feasible, but will require exceptionally large amounts of energy and special equipment, resulting in higher capital costs [31]. Higher capital and operation costs per ton of rock may also be expected due to longer processing times in the mills. Furthermore, production of ultrafine particles will require precautionary measures to avoid respiration of particles, which could cause pulmonary diseases as observed for mineral dust in the agricultural sector [32]. Avoiding those risks through technical measures could cause additional costs [33].

Assuming a carbon price that rewards removing carbon from the atmosphere, it can be shown that an optimal grain size exists, that maximizes profits as a function of carbon price (SI E). We find that the optimal grain size decreases with increasing carbon price, making grain sizes $<50\,\mu$m profitable. To elucidate the effect, all presented data are calculated based on four different grain sizes: 50 μm as an upper boundary, 20 μm as a typical and technically rather easy to achieve diameter, 10 μm, which was used e.g. in [13], and 2 μm as a lower boundary (technically and regarding health implications).

Mining, crushing, and grinding. Costs for mining, crushing, and grinding consist of specific investment costs, operation and maintenance (O&M) costs, and energy costs. To assess the range of expected values for investment and O&M costs, selected economic assessment reports for open-pit mines were analyzed, resulting in a best estimate of 5.0 US \$ t^{-1} rock and 25.1 US \$ t^{-1} rock, respectively (figure 4(*a*); detailed overview can be found in SI J). The specific energy demand for mining and crushing is only 0.01–0.03 GJ t^{-1} rock [34] and, thus, negligibly small. The electricity demand for grinding depends strongly on the target grain size, with a best estimate ranging from 0.07 GJ t^{-1} rock for 50 μm to 3 GJ t^{-1} rock for 2 μm (SI C). Electricity prices can vary significantly by region and over time. For the purpose of our

first-order cost estimate of the EW technology, we take the 30 year mean of the regional median electricity price of 23.8 US $ GJ^{-1} [35]. Figure 4(*a*) shows the resulting costs for comminution energy.

Transport and distribution. Costs for transportation to and spreading the ground rock on cropland consist of fuel (diesel) costs and specific costs e.g. for labor. Both are a function of mass, but not of grain size. We assume decentralized sourcing of rock material, using locally available rock with large enough potential to remove CO_2 (SI L). Nonetheless, transport costs will increase considerably when more remote fields must be used, forced by the extended deployment of EW. Transport costs may significantly vary by region. We therefore evaluate transport distances for the regions given in SI table I-1.

To evaluate the costs for material transport from the rock source to application areas, transport distances per region and grade (i.e. warm and temperate) are calculated (SI K). Global transport distance as a function of accumulated cropland area shows that 80% and 95% of available areas are within 300 km for temperate and warm regions, respectively (figure 4(*b*)). Transport may be either by road, rail, or ship. The relative shares will vary over region and time. For an upper estimate of transport costs, we use the cost estimate for transport on road of 0.05 $ km^{-1} t^{-1} [25] for all transport. Estimates for rail and ship transportation are by a factor of 2 and 50 cheaper, respectively [25, 36], but transfer costs to the road for final transportation would also need to be considered. Cost estimates for the final distribution of ground rock to the field are derived from fertilizer application data. Since fertilizer is applied at much lower mass per area than the targeted amount of rock for EW, the best estimates of 12 $ t^{-1} rock and 14 $ t^{-1} rock for O&M costs and fuel costs [37], respectively, should be seen as upper limits. A summary of all estimates is given in figure 4(*a*). Total costs at 300 km transportation amount to 76 (73/82/143) $ t^{-1} rock for a grain size of 20 (50/10/2) μm (SI J).

5. Supply curve

We derive a supply curve for CDR by EW, assuming that there are no bottlenecks on the supply side of the minerals. Furthermore, we assume no adjustment costs for expanding the deployment of EW, and a constant electricity price as specified in section 4.

The supply curve for CDR by EW maps the various opportunities for undertaking the necessary investments and operations onto the marginal costs. For each marginal cost level, the economic potential can be identified. The shape of the supply curve depends on the parameters and geo-spatial conditions introduced above. Due to the large uncertainties afflicting the CDR potential, we derive a relative supply curve that describes the costs for reaching a certain

percentage of the total potential. The remaining uncertainty shown in figure 5 is purely economic.

The supply curve presented here describes the steady state, where the maximum potential per grade is used each year. It does not describe the transition phase in the beginning when fields are gradually filled up or in the end when EW is phased out again. The time it takes to reach the steady state depends on the weathering rate. In a scenario with low weathering rates, a steady state is reached after a longer time period, decreasing the overall potential of the method and making it less likely to be considered in CDR portfolios. Figure 5 shows the global supply curve for dunite and basalt for four different grain sizes, 2, 10, 20, and 50 μm and the relative regional distribution of carbon removal. Regional supply curves are given in SI M. Costs depend on the amount of rock ground and spread and on the grain size. Therefore, the difference in costs for carbon removal between basalt and dunite is only due to their different carbon sequestration potential. Due to increasing distance from mine to field, costs increase towards higher carbon removal. For grain sizes larger than 10 μm, the weathering potential decreases, but effects on costs are minor. Marginal cost curves for 10 and 50 μm are well within the uncertainty range of the curve for 20 μm (figure 5). Costs only start to change significantly at very fine particle sizes below 10 μm. Our results show that the highest potential for EW is in low latitudes including large areas in Brazil (BRA), India (IND), South-East Asia (OAS), and China (CHN). Temperate regions like the EU offer potential as well but play a minor role, with about 3.6% of the global potential.

Our analysis does not cover potential CO_2 that is emitted during mining, grinding, and spreading of rock powder, which leads to a CO_2 penalty, decreasing the overall net CO_2 sequestration. Given the fact that EW would only become economic at carbon prices above 60 $ t $CO_2{}^{-1}$, it seems highly unlikely that it would be used with carbon-intensive energy production [38]. If electricity were produced with fossil fuels, the carbon penalty for comminution would be about 0.02 t CO_2 t rock^{-1} assuming an energy input of 0.2 GJ t^{-1} (potential reduction by 2%–7%). Further carbon penalties from the supply chain are at least an order of magnitude lower [8].

6. Discussion and conclusion

The inorganic sequestration of CO_2 by EW will only be considered as a relevant CDR option if it is economically competitive within a climate policy framework, not harmful to the environment, and able to remove significant amounts of carbon from the atmosphere. In our study, we limited our assessment to croplands. Taking into account additional areas, e.g. forests would increase the global CDR potential, but could increase costs by a factor
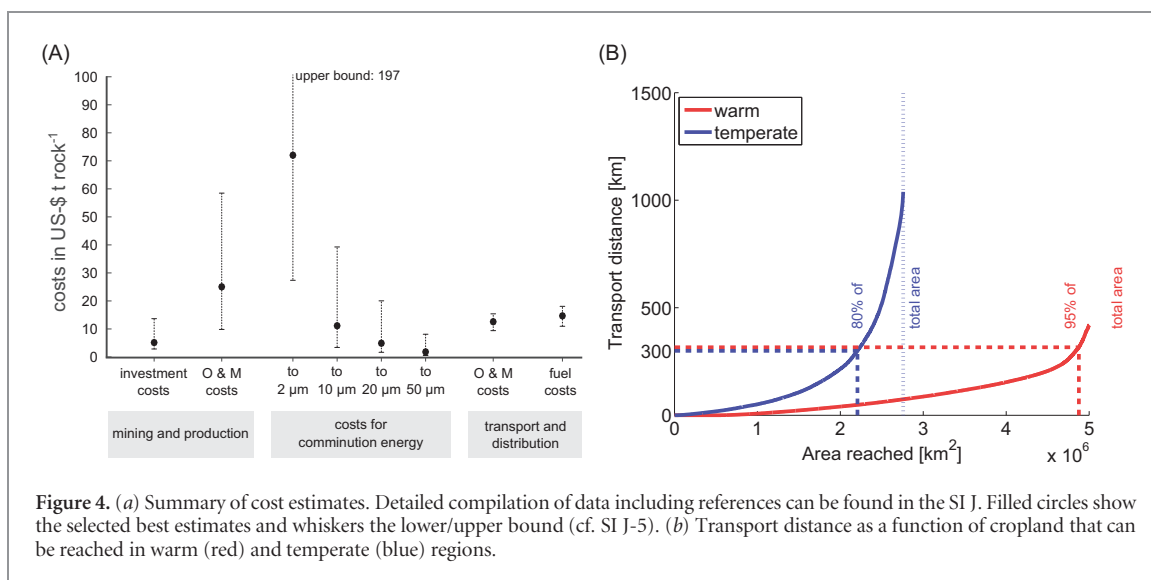
Figure 4. (*a*) Summary of cost estimates. Detailed compilation of data including references can be found in the SI J. Filled circles show the selected best estimates and whiskers the lower/upper bound (cf. SI J-5). (*b*) Transport distance as a function of cropland that can be reached in warm (red) and temperate (blue) regions.
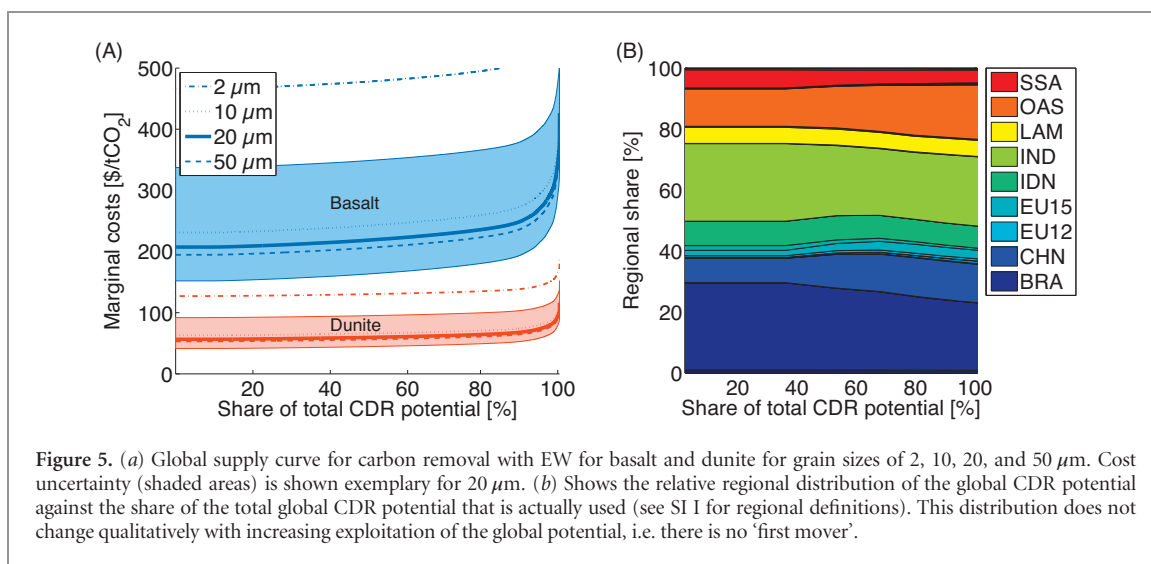
Figure 5. (*a*) Global supply curve for carbon removal with EW for basalt and dunite for grain sizes of 2, 10, 20, and 50 μm. Cost uncertainty (shaded areas) is shown exemplary for 20 μm. (*b*) Shows the relative regional distribution of the global CDR potential against the share of the total global CDR potential that is actually used (see SI I for regional definitions). This distribution does not change qualitatively with increasing exploitation of the global potential, i.e. there is no 'first mover'.

of 2–4 [5], thus reducing competitiveness for these areas. With this prerequisite and assuming a limited amount of rock per area, the total potential is primarily determined by the CDR rate, which in our model depends only on the rock material and its grain size.

We assessed two rock types, dunite and basalt. Basalt is an abundant rock type with a lower yet sufficient sequestration potential and considerably fewer trace element levels than dunite. In addition, basalts are on average rich in nutrients such as phosphorus, magnesium, and calcium, whose application on cropland could lead to considerable additional benefits [3, 39–41]. These are particularly interesting in the case of tropical regions where cation and geo-nutrient depleted soils feature deficits considering optimal plant growth rates leading to recent efforts to assess rock product fertilizer alternatives [42], which could also improve soil hydrology. Furthermore, projected shortages in K supply (as potash) could shift the focus to alternative rock products [43]. The enhancement of CO_2 sequestration in biomass or soil organic carbon

increase could add a further dimension in the economic analysis framework.

A large-scale deployment of EW for CDR would require a considerable effort in mining and transport. To sequester $1 \, Gt \, CO_2 \, a^{-1}$, more than 3 Gt basalt would have to be spread each year. While this is a very large amount, it still seems feasible considering that it is well below the magnitude of global coal production, which exceeded $8 \, Gt \, a^{-1}$ in 2014 [44]. However, large parts of the potential are realized in developing countries, where extensive mass transport for EW could have a substantial effect on their transport system.

Another reason for concern could be the creation of fine dust particles if the target grain size is strongly decreased to compensate for low weathering rates. Even at grain size targets above 10 μm, a certain share could be below this threshold [31], which implies potential health risks from respiration [32]. One possibility to overcome this problem would be the creation of a slurry to keep small particles on the ground.

We found that a significant global annual CDR potential of $4\,\text{Gt}\,CO_2\,\text{a}^{-1}$ can be reached using either dunite or basalt, without considering the biologically induced additional carbon storage. This carbon removal would require weathering rates to range between $10^{-9.95}$–$10^{-11.5}$ and $10^{-10.75}$–$10^{-11.95}\,\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$ for basalt and dunite, respectively, at a grain size of $20\,\mu m$. For lower natural weathering rates, the grain size would have to be decreased to reach a similar potential.

EW will only be deployed at a larger or even global scale if it is economically competitive within a climate policy framework. We assessed economic costs to be below $70\,\$\,\text{t rock}^{-1}$ for grain sizes around $20\,\mu m$, leading to costs of carbon removal around $60\,\$\,\text{t}\,CO_2^{-1}$ for dunite and around $200\,\$\,\text{t}\,CO_2^{-1}$ for basalt. This is higher than most recent cost estimates for afforestation ($24\,\$\,\text{t}\,CO_2^{-1}$, [45]) and BECCS ($36\,\$\,\text{t}\,CO_2^{-1}$, [45]), but still lower than expected costs for direct air capture (430–$570\,\$\,\text{t}\,CO_2^{-1}$, [45]). If co-benefits from nutrient supply or soil improvement are taken into account, the competitiveness of EW will be further increased. However, parameters to achieve an economic assessment of nutrient supply still need to be compiled.

The literature results hint towards major uncertainties in the estimation of CO_2 consumption from weathering, underscoring the need to improve models including hydrological as well as biological processes affecting the rate estimate. A further dimension to be addressed in the future is the influence of soil hydrology and preferential water flow paths, as rock-water contact times are a relevant factor [46, 47]. In addition, the soil CO_2 production rates as a pH regulator besides organic acids need to be evaluated spatially explicitly to be able to model the evolution of fluid saturation and its kinetics within the soil column. We conclude that large uncertainties remain, especially regarding the weathering rate under natural conditions and the overall carbon sequestration potential including biogeochemical effects. Here, more research is required to better determine the potential of EW.

Given that co-benefits from nutrient supply could make EW economically more competitive and considering the increasing importance of sustainability concerns, EW could be an attractive climate change mitigation option, especially for (sub-)tropical countries and regions, like India, Brazil, South-East Asia, and Southern China. These regions have the highest potential for application, considering suitable land and increased temperatures to ensure a rapid weathering process. Since these regions are key players in the international climate policy arena, the consideration of EW as a CDR option might have significant implications for the implementation of the Paris Agreement. For a better understanding of the climate policy impact of EW, more work is needed to reduce the large uncertainty about regional CDR potential, which strongly depends on weathering rates and more specifically the potential additional storage of carbon in biomass due to fertilization.

Acknowledgments

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