Potential CO2 removal from enhanced weathering by ecosystem responses to powdered rock

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Negative emission technologies (NETs) underpin socioeconomic scenarios consistent with the Paris Agreement. Afforestation and bioenergy coupled with carbon-dioxide (CO_2) capture and storage are the main land NETs proposed, but the range of nature-based solutions is wider. Here, we explore soil amendment with powdered basalt in natural ecosystems. Basalt is an abundant rock resource, that reacts with CO_2 and removes it from the atmosphere. Besides, basalt improves soil fertility and thereby potentially enhances ecosystem carbon storage, rendering a global CO_2 removal of basalt substantially larger than previously suggested. Because this is a fully developed technology which can be co-deployed in existing land systems it is suited for rapid upscaling. Achieving sufficiently high net CO_2 removal will require upscaling of basalt mining, deploying systems in remote areas with a low carbon footprint, and using energy from low carbon sources. We argue that basalt soil amendment should be considered a prominent option when assessing land management mitigation options for mitigating climate change, but yet unknown side-effects, as well as limited data on field-scale deployment, need to be addressed first.

Rapid and massive deployment of negative emission technology (NETs) to remove carbon from the atmosphere is needed if we are to achieve the climate stabilization targets agreed at the 2015 Paris Agreement[1]. A range of nature-based NETs have been proposed which offer the advantage of low technological barriers and modest energy demands. However, their potential and scalability[2] are uncertain and some compete with other land uses for land, water and nutrients[3,4].

Nature-based land NETs rely on biomass carbon sequestration through interventions such as planting forests, sustainable forestry, soil carbon sequestration from increased inputs to agricultural soils and biochar additions, and the enhancement of weathering. Enhanced weathering offers the advantage that it can be deployed with other land uses. Yet, there are few studies about this NET[3–6] and to our knowledge, regional and global scalability were only investigated for arable land[8], with co-benefits for biomass and soil carbon sequestration remaining largely omitted. Here, we focus on one specific and promising application— the amendment of soils with basalt dust (BD). This choice is justified by the vast availability of basalt[9], its high weatherability[10], and co-benefits[5,11].

Basalt soil amendment

Soil amendment is the addition of any material to a soil to enhance its functioning or, in other words, its suitability for a given use. Here, we consider the enhanced weathering from BD to accelerate the reaction of atmospheric CO_2 with the silicates contained in basalt[12]. The silicate grains chemically react with CO_2 to form bicarbonate dissolved ions; these are transported by rivers to the oceans and potentially stored for hundreds years and longer, depending on calcium carbonate sedimentation processes[13]. In addition to this abiotic carbon dioxide removal (CDR) pathway, amending soils with BD enhances soil fertility by releasing nutrients, buffering low soil pH, stabilizing soil organic matter[14], and can improve soil water retention[15], thereby promoting plant growth and CDR in agriculture[16–18] and forestry[11]. This biotic CDR pathway for enhanced weathering[19,20] has so far been omitted in assessments of the climate mitigation potential of this NET[6,21].

Basalt dust has mainly been considered for application in agriculture[5,8,22], less so in forestry,[23] and occasionally in natural ecosystems and ecosystems under restoration[6]. Yet, biomass production and carbon storage in a wide range of unmanaged systems[24–27] is limited by essential nutrients, such as phosphorus or potassium, which are contained in basalt. In several regions the positive effect of elevated CO_2 on biomass production hinges on the availability of phosphorus[28]. Thus, BD amendment could deliver additional phosphorus to sustain or even increase biomass production, and subsequent CO_2 removal, in not only managed but also in natural systems.

Carbon dioxide removal potential

To illustrate and explore the full CDR potential from BD application for present-day conditions, we used a land surface model (ORCHIDEE-CNP) which resolves weathering processes and how the release of phosphorus stimulates ecosystem carbon sequestration. This model includes a simplified weathering module calibrated against data available from short-term studies, in view of the scarcity of long-term field-scale experiments[22,29,30]. We used an idealized scenario in which a single BD dose was applied to global vegetated hinterland (i.e. travel distance of >3h from next small city or town)[31] (Supplementary Figure S1) where the likelihood of interference with human activities is low (less than 1% of global populations lives in hinterlands)[31] . It is not intended to reflect realistic deployment scenario, but was chosen to identify sparsely populated regions with high CDR potential. We also performed a baseline simulation without BD application. We analyzed the average biotic and abiotic CDR over five decades after a one-time BD application. A particle size was chosen such that it dissolves within five decades after application under most conditions (Extended Data Fig. 1). See Methods for a description of the model, the experimental design, and details of the analysis.

We found that the application of 5 kg m^{-2} of BD over a hinterland area of 55 million km^2 results in a CDR potential of 2.5 Gt(CO_2) yr^{-1} over 50 years. This is somewhat higher than an earlier estimate for croplands of ~2Gt(CO_2) yr^{-1})[22] for a comparable amount of BD (~ 6 Gt) but a much smaller area (~8 million km^2), which did not account for biotic responses. The biotic pathway contributes about half (40–58%) of global CDR (Fig. 1). With increasing BD application, less CO_2 is removed per amount BD added (Extended Data Fig. 1 & 2, Supplementary Fig. S2), which suggests a general limit to the extent that CDR can be augmented by adding larger amounts of basalt to soils. Regionally, we find that the biotic pathway contribution to CDR is highly variable (32–80%; i.e. 25th – 75th percentile of data lumped from all 9 BD experiments) (Fig. 2a,b) and is more influenced by ecosystem type than application rate, basalt P content (Supplementary Fig. S3 & S4) or climate zone. The strongest biotic CDR occurs in tropical regions on phosphorus-depleted soils where the addition of phosphorus in basalt enhances wood production and biomass carbon storage (Supplementary Text S1.2, Supplementary Fig. S6). In Siberia, a high biotic CDR is predicted in regions where P released from BD enhances background P inputs by several orders of magnitude (Supplementary Fig. S5). The few available mineral P fertilizer experiments indicate positive biomass responses in boreal systems[26].

Limitations and concerns

A major limitation to achieving the full CDR potential is the economic cost of mining, crushing, and grinding basalt, and applying BD on targeted areas[22]. Under the conservative assumption of no technological innovation, we derived a supply cost curve for CDR by BD applied by helicopters or fixed wing aircrafts equipped with agricultural spreaders [32-35] which are used to spread basalt in the form of free-flowing dust[35] or slurry[34] and have low requirements for ground infrastructure. Modified large aerial tankers such as those currently used for firefighting have >10 times the range and carrying capacities of small aircrafts and could provide means to spray dust on large areas. We also assume that there are no bottlenecks on the supply side of basalt (Fig. 3). We estimated that a global average of 0.2 Gt(CO_2) yr^{-1} could be removed over a period of 50 years for regional costs lower than 100 US\$ t^{-1}(CO_2) and up to 2.5 Gt(CO_2) yr^{-1} in a more costly scenario for ~500 US\$ t^{-1}(CO_2) (Tab. 1). The average costs are generally higher than estimates for BD deployment in agriculture and in coastal zones ranging between 50-200 US\$ t^{-1}(CO_2) [8,21,22], due to higher application costs . Modes of application other than by aircraft could help to reduce costs greatly, although substantial investment in the development of technologies such as airships and drones or alternatives like railways and pipelines would be needed. If only abiotic CDR is considered as in previous assessments, the costs would exceed 550 US\$ t^{-1}(CO_2) (Fig. 3). Thus, the additional carbon sequestration in ecosystems from the release of phosphorus is critical to make this technology competitive.

The second limitation is the extra greenhouse gas (GHG) emissions associated with the mining, crushing, grinding of rocks, and their distribution, which will partly offset the CDR benefits[8,36]. Based on a compilation of present-day GHG emissions[37] for freight transport and energy generation (see Methods), we found that such emissions depend on the mode and distance of transportation, as well as on the energy production system in the NET technological chain. In contrast to cropland application[8,22], the spreading and transport of basalt are the dominant source of GHG emissions even if coal is used for energy generation (Extended Data Figure 3 & 4). If BD were to be applied using aircraft, the GHG emissions from air transport would offset the median CDR benefits (280 kg(CO_2) t^{-1}(basalt)) for distances >450 km from airports (Extended Data Figure 3, Supplementary Fig. S8), but regionally substantial net negative emission could still be achieved even for remote (>1000 km) regions where CDR potential is high (e.g. Amazonia, Siberia; Fig. 2a, Supplementary Fig. S2). GHG emissions from transport and deployment of basalt depend on distance and transport technology (0.5-62 kg(CO_2eq) t^{-1}(basalt) 100 km^{-1}). The emissions from the energy mix used for producing BD as well as emissions from building infrastructure (0.6 - 46 kg(CO_2eq) t^{-1}(basalt)) are of secondary importance unless target sites are close to mines (Extended Data Figure 4). Note that these are conservative estimates, as GHG emissions can be expected to decrease over time due to innovation and progress in renewable energy transition.

A source of concern is the environmental impact of massive BD deployment in natural systems: although positive impacts have been suggested[8,15], the effects of BD application on eutrophication of aquatic systems, on biodiversity, on biosphere-atmosphere feedbacks, and on air-, water- and soil pollution still requires thorough assessment. Moreover, application of fine (<10 µm) particles may also pose health risks[32]. Depending on how and where BD is deployed, negative side-effects could include albedo changes, damage to plant and wildlife tissue, and BD losses from wind transport[38]. Therefore, pre-treatment of BD (e.g. pellets, coatings, or suspensions)[30,34,35] and use of repeated application of smaller doses should be explored to reduce some of the potential negative side-effects. While soil pollution can be avoided by choosing basalt with low pollutant content or pre-treatment[30], risks related to affecting river chemistry and biodiversity do not only depend on the dose of BD, but also on the ecosystem status and on the fate of the P released from BD. Based on our exploratory modelling, we find low risks for negative effects of P leaching on water quality for most aquatic systems for addition of 5 kg(basalt) m^{-2} or less (Supplementary Text S3, Extended Data Figure 5 & 6), but field scale experiments are needed to validate our findings. Potential positive side-effects are alleviating deficiency of plant nutrition, and reduce nitrous oxide emissions and nitrogen leaching[5], in regions affected by the extermination of wildlife[39] and high anthropogenic nitrogen deposition[40,41]. The impact on terrestrial biodiversity is difficult to assess due to scarce data. In general, positive relationships between bacteria, invertebrate and tree diversity and soil phosphorus or potassium content are reported for a wide range of ecosystems[42–43], while negative impacts have been shown for grassland communities[44]. Targeted field scale experiments are needed to assess the response of biodiversity to rock powder additions and associated inputs of plant nutrients.

Scalability and barriers

Basalt dust amendment was here re-appraised as a promising NET that could be leveraged to help reach ambitious climate targets, given its previously overlooked enhancement of biological carbon sequestration. Several aspects of this technology advocate for rapid upscaling. First, it can be co-deployed, minimizing interference with other land-uses. Second, there are clear co-benefits for other land-uses such as: crop and fibre production[5,15–18], the revitalization of the natural phosphorus pump[45], the alleviation of anthropogenic stochiometric imbalances[41] and soil degradation[46]. These provide incentives for BD application in managed and natural ecosystems. Third, extracting basalt and applying BD at large scale would provide a new market for the mining industry currently suffering overcapacity and the accumulating overburden material[19]. Basalt mining could also replace jobs in the declining coal mining sector, facilitating just transitions towards renewable energy[47]. Lastly, a mix of basalt and waste products like phosphate gypsum and alkaline industrial waste (e.g., steel slag or concrete from demolition[8]) could be used – following the idea of the inevitability of a transition toward a regenerative Circular Economy (as acknowledged by China, Japan, Canada, and the EU[48]). Our findings show that to sustain a global CDR of 1.3 Gt (CO_2) yr^{-1}, a minimum amount of 1.1 Gt yr^{-1} basalt is sufficient (Table 1) if applied to regions with the largest CDR potential (not accounting for carbon emissions from production and deployment of BD). This indicates the possibility of a higher CDR per unit mass of basalt than for cropland application[8].

Several societal, political, environmental and technological barriers would need to be overcome before a widespread deployment of BD amendments could be implemented. First, criteria for the selection of deployment sites and monitoring of CDR for carbon crediting would need to be established from science-based transparent evidence, as the efficiency of CDR is very variable among regions. Mining sites should be optimally allocated to application areas for maximal CDR, maximal cost and emission efficiency, while taking the constraints on transport infrastructure into account. This would require not only substantial investment in transport and renewable energy infrastructure for the mining industry, but also in new technologies which would allow heavy cargo to be delivered to and spread over remote locations with a low CO_2 footprint. Alternatively, ground-based deployment networks in combination with energy-efficient long distance 'slurry pumps' as currently operated in the mining sector[49] could be used. Uncertain environmental risks and benefits associated with the release of trace elements in BD (e.g., heavy metals and plant nutrients) for land, freshwater and coastal systems need to be considered. Besides the ongoing field trials in agricultural systems, the deployment in degraded forest and in afforestation/reforestation sites on impoverished or degraded soils should be tested to assess weathering and CDR efficiency and environmental issues. Regions where anthropogenic nitrogen deposits have promoted deficiencies in plant nutrition and soil acidification are of particular interest[40]. Lastly, societal and political barriers[3,8] need to be addressed. In particular, public engagement is needed to overcome the extremely low public awareness of this technology[50]. An initial use of BD in agriculture, ecosystem restoration and afforestation may help to facilitate societal acceptance of more widespread application. If these barriers can be overcome, BD application in hinterlands could provide an important contribution to climate stabilization targets.

Methodology

Modelling

We applied the global version (revision 5986, v1.2) of the nutrient-enabled land surface model ORCHIDEE-CNP[51]. The model simulates the exchange of greenhouse gases (i.e. carbon dioxide, nitrous oxide), water and energy at the land surface at a half hourly time step , accounting for effects of nitrogen and phosphorus availability on plant productivity and organic matter decomposition. In case of low nutrient availability, plant investment into root growth increases at

the expense of leaf growth while foliar and fine root nutrient concentration is reduced, leading to lower plant productivity and carbon storage. Negative effects of nutrient shortages on plant productivity are partly compensated by higher activity of soil enzymes enhancing plant availability of phosphorus in soil organic matter and reduced losses of phosphorus by leaching due to the low phosphorus concentration in soil solution. The nutrient content of woody plant tissue is assumed to be rigid More information is given in the SI Text 1. The model is well evaluated at site to global scale including nutrient leaching from terrestrial soils and the effects of elevated carbon dioxide (eCO_2) on primary productivity and land carbon storage[51-54]. The response of aboveground productivity to mineral P fertilizer addition compares well to observation-based estimates (SI: Text S1.3).
ORCHIDEE-CNP was coupled to a model for enhanced weathering which simulates the release of phosphorus and base cations from weathering of basalt grains in soils as a function of soil pH, soil temperature, and grain size, and basalt chemistry[22]. The abiotic carbon dioxide fixation pathway is based on the transfer of weathered base cations (i.e. Ca^{2+}, Mg^{2+},K^{+}, Na^{+}) from soil drainage waters to surface waters that are charge-balanced by the formation of bicarbonate (HCO_3^-) ions and transported to the ocean, accounting for effects of ocean carbonate chemistry on carbon dioxide fixation. Due to our focus on the role of the biotic CDR pathway, we omitted the role of ocean heterogeneity[55]. The model was parameterized on dissolution reactions under controlled laboratory conditions. The scarce available data on basalt dissolution under field conditions indicates that rates are of the same order of magnitude as in the incubation experiments (SI: Text S2.2, Table S1). The P release during mineral dissolution is derived from the dissolution rate based on the P concentration of the grain assuming a homogeneous dissolution. A full description of the model can be found in SI: Text S2. Biological CDR is estimated by the differences in land carbon storage and nitrous oxide emissions between simulations with and without BD. Thereby we account for the background carbon sink due to legacy effects of historic changes in CO_2 concentration, climate and land use. BD can cause changes in nitrous oxide emissions due to plant mediated BD effects on soil nitrogen and water, but the effects were found to be negligible in simulations (Figure S2). We assume a conversion factor of 298 to derive CO_2 equivalent from nitrous oxide emissions[57] to include them as part of CDR.

Model simulations were performed using reconstructed climate, atmospheric CO_2 concentration, land use and land management, and nitrogen and phosphorus inputs via atmospheric deposition, synthetic fertilizer and manure application. Information on soil conditions (soil pH, soil texture, bulk soil density) are prescribed from global reconstructions and are static in time. More details can be found in the SI Text 1.1, Table S2. Starting from the year 2018, we ran 50-year simulations with different idealized scenarios of soil amendment with basal dust to all ice-free hinterland[31] excluding large deserts, as well as a baseline simulation without basalt dust application (Table S3).This does not represent a realistic deployment scenario, but is designed to give a first estimate of the full CDR potential of basal dust application in natural ecosystems and to identify regions with high CDR potential. We focus on hinterlands ecosystems, i.e. at a travel distance of more than 3 hours from the nearest small city[31](Figure S1), to minimize potential interference with other land uses and human activities due to the increase in atmospheric particulate matter at the time of application or thereafter. The grain diameter of 20 µm was chosen such that the basalt applied to the hinterland area has mostly dissolved within five decades. Depending on the mode of deployment larger particle sizes are preferable to reduce costs, energy demand of grinding, and environmental-, and health risks. The phosphorus content of basalt varies between geological formations[29,30]. To account for this uncertainty, we conducted 3x3 simulations in which either 1, 3 or 5 kg m-2 basalt dust with three levels of phosphorus content: 0.161±0.135 %-weight (mean ± 1-sigma standard deviation from ref[29]). We used repeated cycles of climate and deposition data for the period 2008–2017, keeping land cover and atmospheric CO_2 concentration fixed to their state in 2017. The initial state of the biogeochemical cycles is taken from ref[53] and accounts for historical changes in atmospheric CO2 concentration, atmospheric nutrient deposition, land cover, and land management (mineral fertilizer and manure) since 1700). We use a grain size of 20 µm, which is cost efficient in the production[22] and penetrates into deeper soil layers through water percolation and bioturbation[57]. For P content we prescribe average +/-standard deviation P of basalt from n=65363 samples in the GEOROC database[29].

Cost analysis

Cost assessment is needed to evaluate commercial feasibility of basal dust and to put a price on climate mitigation actions. The main economic costs for BD are mining, crushing, and grinding of rocks, and transport to and distribution over target areas. Here, we assume application with helicopters or small fixed-wing aircrafts equipped with agricultural spreaders which can carry up to 4 t over a range of ~1000 km[33-35]. Dust is either mixed with water in a ratio of 1:5[33]or as free-flowing particles (size > 500 micro m)[34]. We calculate the costs based on present-day costs compiled by ref[7,8,22]. These estimated costs account for uncertainties with respect to energy costs, airborne application and variation between open-pit mines. Here we briefly summarize the approach - details are listed elsewhere[22]. Costs for mining, crushing, and grinding (c_{mine}) consist of specific investment costs (c_{inv}), operation and maintenance (O&M) costs (c_{OM}), and energy costs (c_{en}): $c_{mine} = c_{inv} + c_{OM} + c_{en}$. The associated costs (range) were extracted from economic assessment reports for open-pit mines: c_{inv}= 5.0 (2.2–8.5) US$ t^{-1} , c_{OM} = 25.1 (15.2–33.5) US$ t^{-1}. The electricity demand for mining and crushing ranges between 0.01–0.03 GJ t^{-1}, and for grinding ranges between 0.069–0.6095 GJ t^{-1} for the target grain size of 20 µm. Electricity prices can vary significantly by region and over time. As a first-order cost estimate, we take the median electricity prices among EU15 and G7 state (27.5 US$ GJ^{-1}) of the year 2018[8]. Costs for ground transportation from mines to airfields (c_{tran}= 8.57-9.21 US$ t^{-1}) and spreading the ground rock by small aircraft (c_{air}=88-171US$ t^{-1}) are a function of mass and consist of fuel costs and specific costs, e.g., for labour and were taken from ref[7]: $c_{appl} = c_{tran} + c_{air}$. Total costs are given by the sum of c_{mine} and c_{appl}: 174 (116 – 239) US$ t^{-1}.

Greenhouse gas emissions from basalt dust

The main greenhouse gas emissions (GHG) are related to the mining, crushing, and grinding of rocks, and transport to and distribution on target areas; these depend strongly on the energy production system[8,20] and transport systems. We collected information on GHG emissions (g (CO_2eq) kWh^{-1}) based on a literature review of life cycle analysis of electricity generation technologies (g (CO_2eq) kWh^{-1} [56] and transport systems (t(CO_2eq $t(rock)^{-1}$ km^{-1}) [58] for the present day (Table SI ST9). The GHG emission can be calculated by combining the energy requirement of mining and grinding of rock material (see above) with the transport distance. The transport distance was approximated by the shortest distance between the nearest location of basal reserves mineable with current technology[9] and the respective model pixel. Fig. SI9 shows the GHG emissions as a function of transport distance for different combinations of transport and energy production systems.

Global mining capacity

The global capacity was approximated using the data for the top five most-mined minerals, namely: coal, iron, bauxite, phosphate and gypsum. A total of 11.78 Gt of rock was mined in the year 2017 [59]. Coal mining is the dominant sector by far (Table SI ST10).

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Author contributions

DSG, PC and TA designed the study. DSG and JC undertook model development and coding, with input from WL and TA. TA provided data on rock chemistry. DSG undertook the data analysis and synthesis. DSG wrote the manuscript with input on sections and addition of appropriate references specific to their area of expertise from all authors.

Data availability

The simulation data (doi:10.5281/zenodo.3963784) (https://doi.org/10.14768/20200407002.1) are freely available. The dataset on airfield location is available at: https://openflights.org/data.html, accessed on 18 January 2020.

Code availability

The source code of the land surface model ORCHIDEE-CNP is freely available (https://doi.org/10.14768/20200407002.1). The authors will make the python codes developed for this study available upon reasonable request.

Competing interests

The authors declare no competing interests.

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Figure 1: **Carbon dioxide removal (CDR) over the five decades after a one-time application of basalt dust to global hinterland.** Three application scenarios are shown: 1, 3 and 5 kg (basalt) m^{-2} for total CDR (colour), as well as for abiotic CDR only (black). The range of CDR per scenario (shaded area) illustrates the uncertainty in phosphorus release from basalt.

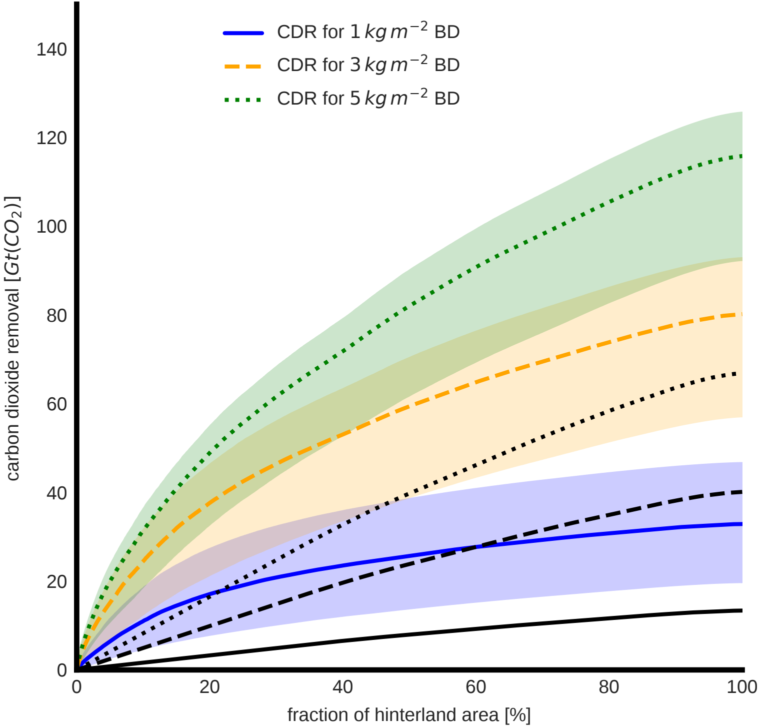
Figure 2: **Spatial pattern of total dioxide removal (CDR) (a), and the biotic contribution (b), of basalt dust application to global hinterland.** a) Carbon dioxide removal (CDR) over five decades after a one-time application of basalt dust of 1kg m^{-2} (simulation A2) and (b) the fraction contributed by the biotic pathway. Blue dots in (a) show locations of near-surface basalt reserves from ref[7].

Figure 3: **Cost of carbon dioxide removal (CDR) over the five decades after a one-time application of basalt dust to global hinterland.** Data points (i.e. model pixels) were ranked according to their marginal costs (from low to high). The horizontal axis shows the respective accumulated share of the global CDR potential. Three application scenarios are shown: 1, 3 and 5 kg (basalt) m^{-2} for total CDR (colour), as well as for abiotic CDR only (black). Cost uncertainty (shaded areas) illustrates uncertainty in costs for mining, crushing, grinding and airborne application.

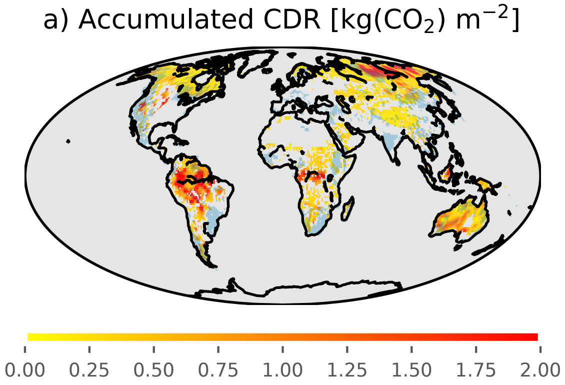
Table 1: Global carbon dioxide removal of basalt dust for regional costs lower than 50, 100, 250, 500, and 1000 US\$ $t(CO_2)^{-1}$ during the five decades after a one-time application of basalt dust to global hinterland. Results of total CDR are shown from the most cost-efficient application scenario. In addition, global average CDR costs as well as the required land area, and amount of basalt dust are given.

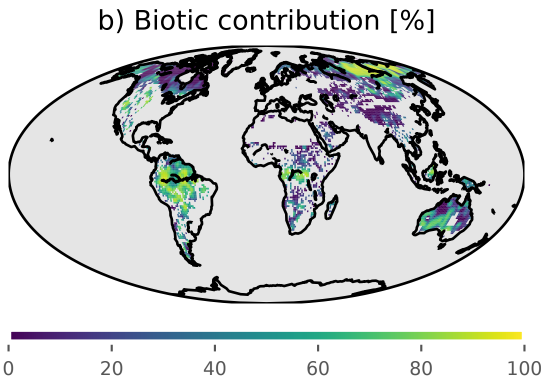
Regional costs	Global average costs	Global carbon dioxide removal	Basalt required	Area required

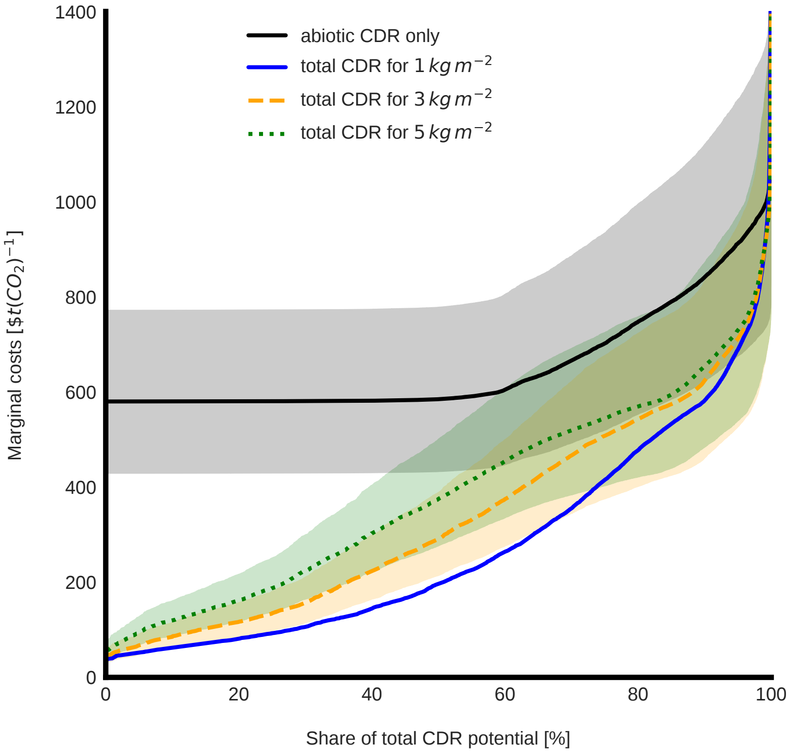
< 100 US$ $t(CO_2)^{-1}$	79 US$ $t(CO_2)^{-1}$	0.2 $Gt(CO_2)\ yr^{-1}$	0.2 Gt yr^{-1}	2 $10^6 km^2$
< 250 US$ $t(CO_2)^{-1}$	156 US$ t(CO2)-1	0.8 $Gt(CO_2)\ yr^{-1}$	0.6 Gt yr^{-1}	10 $10^6 km^2$
< 500 US$ $t(CO_2)^{-1}$	331 US$ $t(CO_2)^{-1}$	1.7 $Gt(CO_2)\ yr^{-1}$	2.5 Gt yr^{-1}	25 $10^6 km^2$
<1,000 US$ $t(CO_2)^{-1}$	513 US$ $t(CO_2)^{-1}$	2.5 $Gt(CO_2)\ yr^{-1}$	5.5 Gt yr^{-1}	55 $10^6 km^2$



CDR for 1 $kg\,m^{-2}$ BD
CDR for 3 $kg\,m^{-2}$ BD
CDR for 5 $kg\,m^{-2}$ BD
carbon dioxide removal [$Gt(CO_2)$]
fraction of hinterland area [%]
0
20
40
60
80
100
120
140
0
20
40
60
80
100


a) Accumulated CDR [kg(CO_2) m^{-2}]
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00


b) Biotic contribution [%]
0
20
40
60
80
100



abiotic CDR only
total CDR for 1 $kg\,m^{-2}$
total CDR for 3 $kg\,m^{-2}$
total CDR for 5 $kg\,m^{-2}$
Marginal costs [$\$t(CO_2)^{-1}$]
Share of total CDR potential [%]
0
200
400
600
800
1000
1200
1400
0
20
40
60
80
100