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Ideas and perspectives: Synergies from co-deployment of negative emission technologies

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Abstract. Numerous publications propose the deployment of negative emission technologies, which intend to actively remove CO_2 from the atmosphere with the goal to reach the 1.5° target as discussed by the IPCC. The increasing amount of scientific studies on the individual potential of different envisaged technologies and methods indicates, that no single method has enough capacities to mitigate the issue by itself. It is thus expected that technology portfolios are deployed. As some of them utilize the same environmental compartment, co-deployment effects are expected. Those effects are particularly important to evaluate with respect to additional CO_2 uptake. Considering soils as one of the main affected compartments, we see a plethora of processes which can positively benefit from each other, canceling out negative side effects or increasing overall CO_2 sequestration potentials. To derive more reliable estimates of negative emission potentials and to evaluate common effects on global carbon pools, it is now necessary to intensively study interrelated effects of negative emission technology deployment CO_2 sequestration potentials while minimizing side effects.

Introduction

As global mean temperatures are projected to increase further, strategies to mitigate climate change in time by decreasing CO_2 emissions seem to slowly take effect (Jackson et al., 2015). Some CO_2 emission pathways include negative carbon emission strategies (Fuss et al., 2014;Fuss et al., 2016;Rogelj et al., 2018), that essentially capture CO_2 from the atmosphere in different ways, storing them on a long term as CO_2 molecules, or as organic and inorganic compounds (Caldeira et al., 2013). All discussed options and technologies have yet to reach the large-scale deployment stage (Minx et al., 2018;Nemet et al., 2018). Most technologies are immature, lacking deep research on the global potential, technical feasibility, economics of deployment, and especially an assessment of the expected side effects (National Research Council, 2015;Fuss et al., 2018).

The proposed negative emission technologies (NET) encompass highly technical engineering solutions as well as methods that rely on natural processes, like growth of biomass (e.g. bioenergy with carbon capture and storage, and afforestation), soil carbon increase, biochar, and chemical weathering (e.g. enhanced weathering and ocean liming). As these methods are aimed to be integrated in global biogeochemical cycles and will redistribute carbon within reservoirs (Keller et al., 2018), their interaction is inevitable if NETs are deployed at the largest scale. As such, it must be assessed how the co-deployment of NETs will affect the individual and overall efficiency, since until now, publications focus solely on single NETs, disregarding any effects on concurrent deployment of additional technologies.

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Findings from NET specific literature suggest that an assessment of effects of combined rollout of NETs is advisable and future research should include CO_2 sequestration enhancing side effects that could increase the overall potential of NETs. However, the principal interaction between proposed methods needs to be studied in detail beforehand, to understand effects on the carbon pools (Fig. 1).

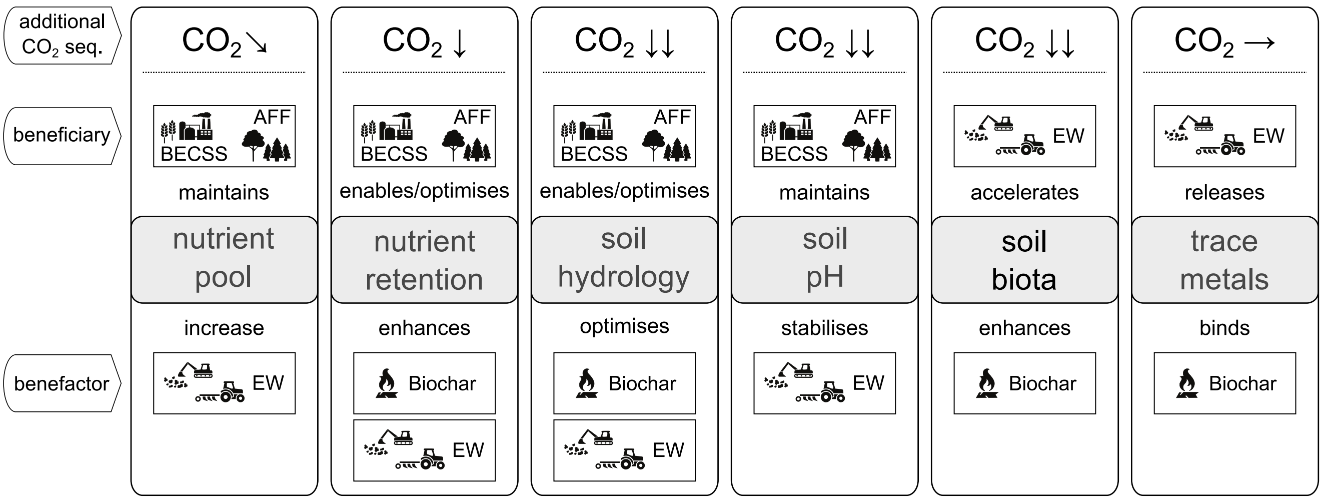

Fig. 1: Overview of effects from combining land based negative emission technologies (Bioenergy production coupled with carbon capture and storage (BECCS), Afforestation (AFF), Enhanced Weathering (EW), and Biochar). Technology symbols courtesy of W. Lamb (MCC Berlin).

Taking the example of Enhanced Weathering, the application of finely ground rock on agricultural land, it is unavoidable that the intended CO_2 sequestration effect by weathering is naturally accompanied by the release of elements with consequences for the environment (Kantola et al., 2017) and consequently the involved carbon pools. The release of elements that are important plant nutrients (e.g., potassium, phosphorus, magnesium, and others) can be beneficial for additional CO_2 sequestration via organic carbon formation. In addition, the soil hydrology can be improved, and cation exchange capacity increased under optimal grain size distribution and mineral selection. In contrast, effects of potentially harmful trace element release (by choosing less suitable material) might be needed to be alleviated. However, an integrated framework to achieve optimization of interrelated effects has yet to be developed, specifically for a global scale management of carbon pools.

To tackle the issue of climate change by negative carbon emission strategies on a global and comprehensive scale, it seems advisable to consider all proposed terrestrial biomass based NETs, like e.g., BECSS, afforestation, and biochar to explore synergistic effects (Fig. 1). A scenario can be envisioned, where rock powder and biochar are applied to agricultural land, which is used for bioenergy plant production (for further use in BECSS technology). Rock material would release geogenic nutrients and biochar could enhance the release of nutrients (Atkinson et al., 2010), and the overall crop productivity (Jeffery et al., 2011). In combination with envisioned and deployed afforestation efforts, which often take place in tropical areas with depleted soils (Nilsson and Schopfhauser, 1995;Grainger, 1988;Zomer et al., 2008), it could be an added, if not essential, benefit: The low capacity of these soils to retain highly soluble industrial fertilisers suggests the use of other forms of slow release fertiliser, like rock dust as a complement (Leonardos et al., 1987;Manning, 2015), or new emerging rock based

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fertilizers (Ciceri and Allanore, 2019), which can, as a side effect, increase the retention of industrial fertilizers, that may still be needed in addition. The ultimate need for an intense management and design of a suitable soil to supply suitable conditions for tree growth can be deduced from a published extreme scenario, which envision large scale afforestation of deserts (Ornstein et al., 2009).

It seems advisable to combine proposed NET methods to achieve an optimal carbon pool management for negative emissions and ensure food security over centuries at the global scale. To achieve this, interdisciplinary efforts are necessary (Fig. 1) and some of the key issues are reviewed here to point out the research direction.

Nutrient pool

Increasing atmospheric CO_2 and an increasing world population will lead to challenges in the nutritional supply of large parts of Earth's population (Smith and Myers, 2018;Myers et al., 2014). In combination with partly declining resources (Manning, 2015 and Suppl. S1), alternative nutrient supplies, i.e. from rock products, are of high interest (Ciceri and Allanore, 2019). This idea has been discussed earlier (Van Straaten, 2006;van Straaten, 2002) and was recently revived in the context of Enhanced Weathering side effects (Beerling et al., 2018). However, this issue extends further, if biomass based NETs are considered for large scale deployment.

Many options of carbon dioxide removal rely on the production of biomass (i.e. biochar, afforestation, carbon capture and storage from bio energy (BECCS), bio fuels). These CDR-methods demand, if driven to an optimum, more geogenic nutrients as typically available to plants in the soil-rock-systems in the long-term, specifically in humid, tropical areas, where soils are deeply weathered and show naturally low nutrient contents (Hamdan and Bumham, 1996) that could not supply an additional intense biomass growth. A study of commercially exploited forests in the U.S. points out that intensive harvest scenarios can withdraw more nutrients from the soils than can naturally be resupplied (de Oliveira Garcia et al., 2018), which would also apply to extensive afforestation scenarios.

Due to the desired global carbon sequestration goals, growth rates will likely be driven to the maximum, which implies an increased demand of nutrients. Models already show that N and P limit the carbon sequestration potential (Goll et al., 2012;Kracher, 2017). Nutrient release by Enhanced Weathering can therefore play a relevant role in supporting the high demand. Particular rock types contain, on average, higher K, P (Fig. 2), or micronutrients like Zn or Se. To ensure a balanced supply of the needed elements, it is therefore necessary to consider not one specific rock type (like before dunite (e.g. Schuiling and Krijgsman, 2006;Hangx and Spiers, 2009) or basalt (Strefler et al., 2018)) but a mixture of locally available material. Optimising the nutrient composition may come at the price of inorganic carbon sequestration potential reduction as some rock type with high nutrient content have low sequestration potentials (Fig. 2).

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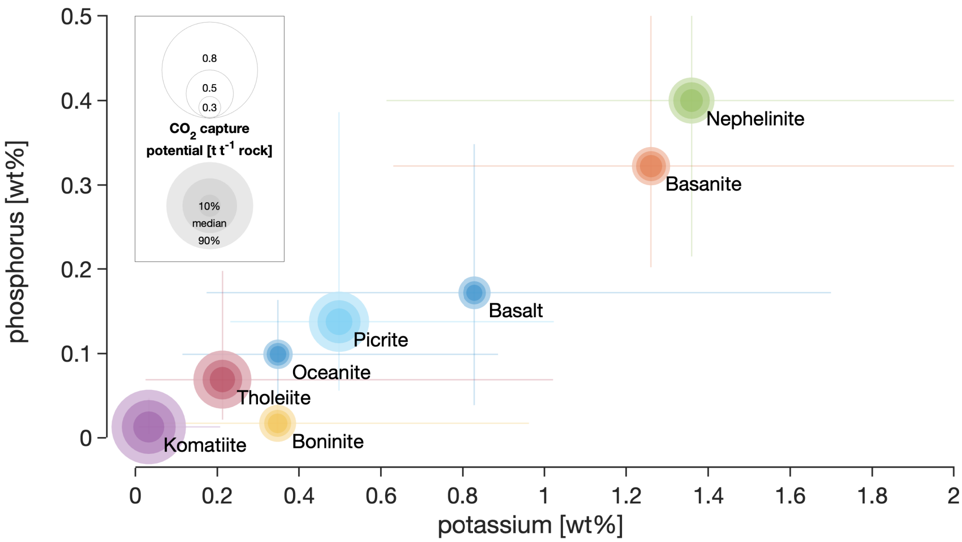

Fig. 2: The averaged K and P contents of selected volcanic rocks in combination with their potential to capture CO2. All shown rocks are selected for a net positive sequestration effect based on the optimistic emissions scenario from Moosdorf et al. (2014). The discussed dunite contains so little P and K that it cannot be shown in the figure (< 0.01 wt% each). Statistical data for shown rocks are from the GEOROC database (Sarbas, 2008), details in Supplement S2. Documentation on CO_2 capture potential calculation in Supplement S3.

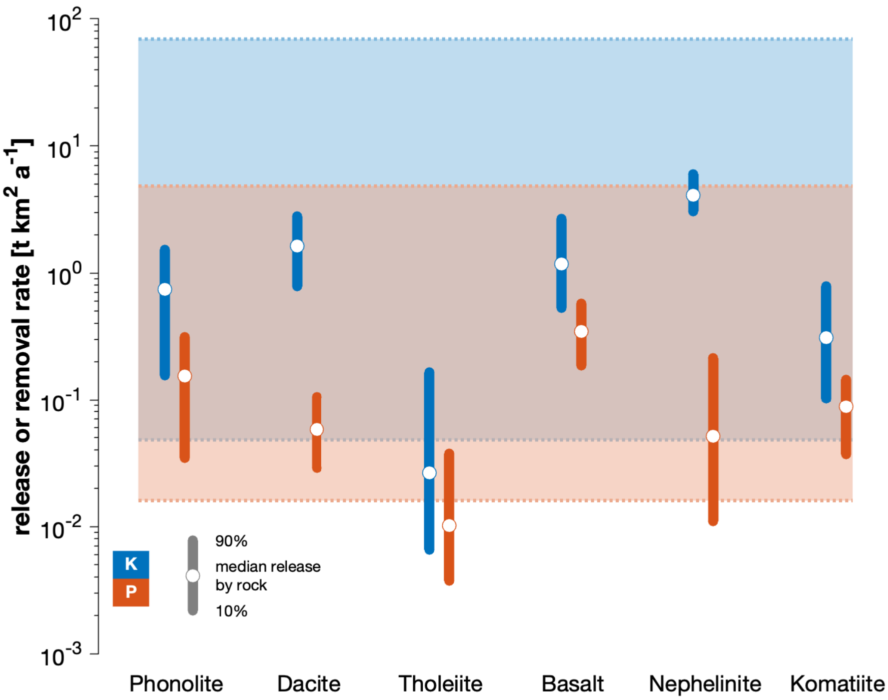

Fig. 3: Weathering release rates (circles; bars as variability indicator) of P and K from selected rocks (assuming their full dissolution under a natural subtropical weathering scenario) and extraction of those nutrients by harvesting Miscanthus energy grass (blue/red areas indicate range between min. and max. nutrient content of different Miscanthus species). Details on rock dissolution and nutrient release rates in Suppl. S4 and on plant nutrient removal and additional to Miscanthus data on major crops in Suppl. S5.

Considering extreme scenarios of biomass plantations (e.g. in Boysen et al., 2016), the intense extraction of nutrients needs to be accounted for (globally more than 8 Mt P and K per year; c.f. nutrient removal from cropland Suppl. S4).

The introduction of additional nutrients to the soil system will not necessarily lead to an additional CO_2 uptake and increased CO_2 sequestration potentials of biomass based NETs, if enough nutrients are supplied by fertilisation. However, forest areas may benefit from slow release long term available nutrients as they may be less easy to be re-supplied on a regular basis by agrotechnical machinery. Also, industrial fertiliser may be unaffordable in low income regions, thus rock products could replace parts of the fertiliser.

Nutrient retention

There are further potential effects that contribute to the overall amelioration effect of rock powder. It has been shown that the cation content of basaltic material increases the cation exchange capacity, leading to an increased retention of nutrients (Anda et al., 2013, 2015). This is especially important for regions where nutrients from industrial fertiliser material are quickly washed out, e.g. in the deeply weathered soils (e.g. oxisols) in tropical regions (Leonardos et al., 1987;Ciceri et al., 2017). In such settings, it will be favourable to establish improved soil conditions with optimised nutrient retention.

Another application case is the fertilisation of forests, specifically on areas which are re-forested after agricultural use. With increasing atmospheric CO_2 concentrations, an increase in biomass productivity on non-agricultural areas is expected through the CO_2 fertilisation effect (e.g. Ciais et al., 1995;Körner et al., 2007;Norby and Zak, 2011), especially with regard to afforestation efforts and general tree growth. This effect is yet to be clearly shown (Leuzinger et al., 2011), and likely to be limited by soil fertility (Oren et al., 2001;Bader et al., 2013). It can already be observed that nutrients provided by rock weathering, like P, K, Mg, and Ca, can be limiting tree growth under elevated atmospheric CO_2 (Jonard et al., 2015). Woodland soils might be amended with selected minerals or rocks to supply sufficient nutrients to keep up growth under elevated atmospheric pCO_2 conditions and organically bind carbon, a scenario that should be explored further for its potential to enlarge affected carbon pools. At some point, depending on the environmental setting, biomass growth will be limited by nutrient supply and as such, model outputs for CO_2 sequestration potentials of afforestation are likely to be overestimated, if geogenic nutrient cycles are not included in the assessment.

The CO_2 sequestration effect of afforestation is even larger if soil organic carbon changes are taken into consideration: Depending on the underlying lithology, the organic carbon pools can be influenced (Li et al., 2017), a process that may be optimised by the spreading of selected rock products.

Overall, specific element deficits need to be mapped, an issue that is increasingly addressed with a focus on human nutrition (Zhang et al., 2017;Hengl et al., 2017;White and Zasoski, 1999). It is necessary to be able to predict, which application amounts of elements causes a certain response in the biomass pool above and below ground. Such data are still scarce and inconclusive (Manning, 2010) but are needed if Enhanced Weathering should be used as a method to help manage carbon pools.

Increased nutrient retention may increase the overall CO_2 sequestration potential of biomass based NETs through the long term availability of nutrients. However, the order of magnitude of the effect remains to be shown.

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Soil hydrology

Spreading large amounts of rock products with too small grain sizes on land potentially leads to a decrease in soil hydraulic conductivity, which may lead to decreased weathering speeds due to local pore water oversaturation or enhanced surface runoff. However, there are some indications that biochar can be used to control hydraulic conductivity (Masiello et al., 2015;Barnes et al., 2014), which could enable the use of smaller grain sizes for Enhanced Weathering, enhancing its potential, which strongly depends on the grainsize (Strefler et al., 2018).

Biochar could also be used to improve the water holding capacities of soils (Omondi et al., 2016;Liu et al., 2017), and also increase the plant available water in some cases (Masiello et al., 2015). This may render dryer regions or areas with unfavourable soil physical properties (Basso et al., 2013) usable for bio energy plants and/or afforestation. There are also indications that improvement of soil hydrology by biochar may increase yield potentials (Akhtar et al., 2014;Xu et al., 2015;Al-Wabel et al., 2018)

It is important to point out that all potential changes of soil physical properties due to biochar application strongly depend on its type, more specifically the feedstock and production temperature (Gul et al., 2015). The combination of rock product and biochar application however was not addressed yet, at all.

Soil pH

Soil acidification on heavily used cropland is a problem (Helyar and Porter, 1989), which may lead to a decrease in crop yields. The main reason is the higher mobility of most exchangeable metals at low pH, which decreases logarithmically with increasing pH (Kabata-Pendias, 2010;Robinson et al., 1996;Tack et al., 1996;Harter, 1983), establishing very low levels of exchangeable harmful metals at pH of 6 and higher, with the exception of Arsenic, depending on the oxidation state (Dixit and Hering, 2003). The release of cations from rock flour leads to a soil pH increase. Studies have demonstrated the effectiveness of basalt powder application in raising the soil pH up to 8 and higher (e.g. Gillman et al., 2001;Nunes et al., 2014). The effect is similar to agricultural liming, which is a common practice to counteract soil acidification on cropland (West and McBride, 2005). Despite the fast dissolution rate of carbonate minerals, they are in general until today not considered for Enhanced Weathering scenarios, because of possible carbonate precipitation and subsequent CO_2 release in the ocean (Hartmann et al., 2013) or due to the potential release of CO_2 by excess fertiliser application (Semhi et al., 2000;Perrin et al., 2008). The potential of carbonates in Enhanced Weathering strategies remains to be studied, while silicate application is in the focus of recent research (Taylor et al., 2015). It could be a potential economic benefit to replace agricultural lime by silicate rock flour, bearing in mind that silicate dissolution rates are in general several orders of magnitude lower, with strong variability between different minerals (Lasaga, 1995;Brantley et al., 2008). Thus, the efficacy is decreased due to the slower release rate of cations, but other properties like nutrient retention or soil hydrology might be improved (cf. previous chapter). It remains to be investigated how (fast) the cessation of pH stabilising silicate rock powder application will affect the soils to provide management suggestions. If relatively immobile potentially harmful metals accumulate at elevated pH values over the application period, an excessive and harmful release of toxic substances might occur in case of a future drop of pH due to changes in pH controlling minerals, land use or general environmental conditions. Once the deployment of material rich in trace elements of concern is started, it is obligatory to maintain a stabilised pH environment, strengthening the need for material with low trace element concentrations, where considered to be of concern (requirements may differ depending on ecosystem type).

Assuming that pH stabilisation and beneficial changes in soil hydrology (cf. previous section) are achievable by biochar and Enhanced Weathering a significant additional CO_2 uptake can be expected, based on the effect that soils are made usable for biomass based NETs, that couldn't support sustainable biomass growth before.

Soil biota

Chemical weathering of rocks can be significantly mediated by macro- and microbiota (Schwartzman and Volk, 1989;Uroz et al., 2009;Hoffland et al., 2004;Blouin et al., 2013), although the order of magnitude is a matter of debate (Drever, 1994). This is specifically the case for mycorrhizal fungi and microbes, which create physico-chemical conditions that (Taylor et al., 2015) accelerate the dissolution of minerals. Microbial populations in soils respond to the addition of biochar (Warnock et al., 2007) by providing a refuge for bacteria and fungi (Pietikainen et al., 2000;Saito, 1990), increasing nutrient availability, creating favourable pH conditions and other processes (Lehmann et al., 2011).

Earthworms have been observed to thrive in biochar amended soils (Topoliantz and Ponge, 2005). Increased abundance of earthworms will likely increase bioturbation effects (Carcaillet, 2001;Major et al., 2010), leading to a better distribution of biochar and rock flour in deeper layers of the amended soils, increasing reactive surfaces of mineral grains. Bioturbation might also be a key process to achieve high CO_2 sequestration rates by weathering, through the downward transport of added rock products into deeper soil layers (Taylor et al., 2015).

Trace metals

Soils are an important sink in the environmental cycling of trace metals (Kabata-Pendias, 1993). Besides naturally occurring concentrations, depending on the base rock, the major source of trace metals to soils is agricultural practice, leading to an enrichment due to the application of manure, sewage sludge, fertilisers, and pesticides, which all contain metals to a certain extent (Gonnelli and Renella, 2013). Field studies using sewage sludge as fertiliser have shown a marked uptake by the crops and increased mobilisation of trace metals in the runoff water (Alloway, 2013). Adding to the anthropogenic input, the introduction of additional rock products with increased levels of trace metals could lead to a critical exceedance of environmental thresholds if improper rock material is used. This is however relating to the solubility of minerals within the used rock type and the redox and pH conditions. A soil incubation Enhanced Weathering experiment with olivine application showed only a few occurrences of elevated Cr levels but no Ni increase in the aquatic solution compared to a blank treatment, leading to the conclusion that the soil solid phase will be successively enriched in those elements (Renforth et al., 2015).

The availability of heavy metals to biota remains an issue of ongoing discussion (Nagajyoti et al., 2010). The main elements of concern in source rocks with the highest sequestration potential (ultramafic rocks) are Ni and Cr. Especially the early discussed dunite application for Enhanced Weathering must trigger the discussion about its high Cr and Ni contents (Tab. 1) and is therefore ruled out for large scale application on cropland.

Tab. 1 Statistical data for Ni and Cr in dunites from the GEOROC database (Sarbas, 2008).

Element	mean	median	stdev	min / max	10 / 90%ile	n
	[ppm]					
Ni	2980	2130	5695	320 / 50669	932 / 3337	204
Cr	3554	2609	6803	49 / 80354	1394 / 5039	140

If an application with rocks of high trace metal concentrations of concern is considered, it is necessary to stabilise the soil pH even after cessation of such actions in order to maintain the fixation of toxic elements, because of the strong pH control on metal mobility. A study of long-term sewage sludge application has shown that the pH had to be stabilised by liming in order to prevent phyto-toxicity of Cu and Zn (McBride et al., 2004). Additionally, the metal availability to plants has been shown to be influenced by the soil texture, with marked differences for different elements (Qian et al., 1996). This underlines the necessity to control or specifically design the grain size distribution of the soil to control water content, pH and oxygen content. To further ameliorate the issue, biochar, which has been shown to immobilise heavy metals in soils, depending on feedstock and production conditions (Ahmad et al., 2014;Beesley et al., 2011) could be jointly applied with rock powder. This would mean that potential limitations of fertiliser or rock spreading due to thresholds put in place for environmental protection could be overcome by a sensible management of biochar utilisation. Applying biochar products does not remove elements of concern, but the problem of heavy metal accumulation could be dampened bioremediation through heavy metal accumulating plants (Rajkumar et al., 2012). This in turn could be a potential new source of raw material for industrial use (Schuiling, 2013), though it is likely not applicable on a global scale, since this would compete against food and energy plant production, which is already an issue (Tilman et al., 2009).

The remediation of trace metal effects does not directly affect CO_2 sequestration rates but could overall increase potential deployment areas for Enhanced Weathering.

Synthesis

Looking forward it is likely that a portfolio of options will be established to optimize the sequestration effect and minimize negative impacts. The combination of previously separately studied NETs to increase the sequestered carbon pool should consider the management of biogeochemical cycles and optimize the combined application of Enhanced Weathering and biochar in context of biomass based methods like BECCS and afforestation to maximize carbon capture as well as food production. It is therefore essential to address combined effects of NET co-deployment in future research projects.
As all presented interactions take place in the soil, future research should put a focus on creating an optimized soil product for an optimal long-term sustainable carbon management. We propose that research around biomass based NET interactions becomes the science of artificial soil products, which are most likely created on depleted and degraded soils especially in the

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sub(tropics). It may consist of the locally available "base soil" mixed with charcoal products to enhance hydraulic properties and nutrient retention, as well as rock powder, which raises the soil pH, provides nutrients and sequesters CO_2 at the same time. This engineered and managed soil could increase carbon pools and crop production, while contributing to tackle the issue of climate change. It remains to be studied where suitable material is available at the regional scale. The parameterisation of element release rates permitting a sustainable management are still subject to large uncertainties and the effects of massive rock product spreading will change the soil structure to an extent that remains to be explored.

The introduction of non-authigenic material into the environment, even if of bio- or geogenic origin, will increase the entropy of the system, making it difficult and expensive (energy and economic-wise) to quickly revert back into the undisturbed state, once large-scale deployment started. Thus, the deployment of NETs at the global scale in an order of magnitude that would measurably impact atmospheric CO_2 levels must be seriously weighed. However, the high probability of NET adoption in the near future makes it imperative to create efficient cooperation networks across all involved disciplines in order to conceive the necessary knowledge on actual CO_2 sequestration potentials and century scale global carbon pool changes.

Competing interests

The authors declare that they have no conflict of interest.

Author contribution statements

This article was conceived by the joint work of J.H. and T.A. Both participated in discussions, planning and writing, with the lead of T.A..

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