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Impacts of Enhanced Weathering on biomass production for negative emission technologies and soil hydrology

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Abstract. Limiting global mean temperature changes to well below 2°C likely requires a rapid and large-scale deployment of Negative Emission Technologies (NETs). Assessments so far showed a high potential for biomass based terrestrial NETs, but only few included effects of the commonly found nutrient deficient soils on biomass production. Here, we investigate the deployment of Enhanced Weathering (EW) to supply nutrients to phosphorus (P) deficient areas of Afforestation/Reforestation and naturally growing forests (AR) and bio-energy grasses (BG), besides the impacts on soil hydrology. Using stoichiometric ratios and biomass estimates from two established vegetation models, we calculated the nutrient demand of AR and BG. By comparing the inferred AR P demand to different geogenic P supply scenarios, we estimated that 3 – 98 Gt C of the predicted biomass accumulation cannot be realized due to insufficient soil P supply for an AR scenario considering natural N supply. An amount of 2 – 362 Gt basalt powder applied by EW would be needed to cover P gaps and completely sequester projected amounts of 190 Gt C during years 2006 – 2099. The potential carbon sequestration by EW is 0.6 – 97.8 Gt CO_2 for the same scenario. For BG, 8 kg basalt m^{-2} a^{-1} might, on average, replenish the exported K and P by harvest. Using pedotransfer functions, we show that the impacts of basalt powder application on soil hydraulic conductivity and plant available water, for closing predicted P gaps, would depend on basalt and soil texture, but in general the impacts are marginal. We show that EW could potentially close the projected P gaps of an AR scenario, and exported nutrients by BG harvest, which would decrease or replace the use of industrial fertilizers. Besides that, EW ameliorates soil capacity to retain nutrients, soil pH, and renew soil nutrient pools. Last, EW applications could improve plant available water capacity depending on deployed amounts of rock powder - adding a new dimension to the coupling of land-based biomass NETs with EW.

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1. Introduction

To limit temperature increase due to climate change to well below 2ºC compared to pre-industrial levels by the end of the century, research efforts on negative emission technologies (NET), *i.e.*, ways to actively remove CO_2 from the atmosphere, intensify. Terrestrial NETs encompass, *e.g.*, Bioenergy with Carbon Capture and Storage (BECCS), Afforestation, Reforestation and natural growing forests (AR), Enhanced Weathering (EW), Biochar, restoration of wetlands, and Soil Carbon Sequestration. From these land-based NET options, BECCS, AR, Biochar, and EW can potentially be combined for increasing atmospheric carbon dioxide removal (CDR) (Smith et al., 2016;Beerling et al., 2018;Amann and Hartmann, 2018).

BECCS combines energy production from biomass and carbon capture at the power plant with subsequent storage. Sources for biomass-based energy production are crop and forestry residues (Smith, 2012;Smith et al., 2012;Tokimatsu et al., 2017), dedicated bio-energy grass (BG) plantations (Smith, 2012;Smith et al., 2012) or short rotation woody biomass from forestry (Cornelissen et al., 2012;Smeets and Faaij, 2007). Large-scale AR, as well as bio-energy plantations, require extensive landscape modifications for growing forests or natural regrowth of trees in deforested areas to increase terrestrial CDR (Kracher, 2017;Boysen et al., 2017a;Popp et al., 2017;Humpenöder et al., 2014), and huge quantities of irrigation water (Boysen et al., 2017b;Bonsch et al., 2016). The biomass yields of AR and agricultural bio-energy crops directly correlate with fertilizer application, which in turn could reduce CDR efficiency due to related emissions of N_2O (Creutzig, 2016;Popp et al., 2011) and initiate unwanted side-effects like acidification of soils (Rockström et al., 2009;Vitousek et al., 1997), streams/rivers, and lakes (Vitousek et al., 1997).

Under intensive growth scenarios, nutrient supply is a critical factor. According to Liebig's law of the minimum, supplying high amounts of nitrogen (N) might shift growth limitation to other nutrients (von Liebig and Playfair, 1843). Some U.S. forests already show changes from N-limited to a Phosphorus (P) limited system caused by increases in N atmospheric deposition (Crowley et al., 2012) along with magnesium (Mg), potassium (K) and calcium (Ca) deficiencies (Garcia et al., 2018;Jonard et al., 2012). Poor nutrient supply, related to deficient mineral nutrition, may reduce tree growth (Augusto et al., 2017). Impacts on biomass production due to poor tree nutrition is observed in European forests (Knust et al., 2016) decreasing the carbon sequestration of forest ecosystems (Oren et al., 2001) – a factor rarely included in climate models leading to overestimated CDR potentials.

Specifically, global simulations with a N-enabled land surface model (Kracher, 2017) suggest that insufficient soil nitrogen availability for a RCP4.5 AR scenario (Thomson et al., 2011) could lead to a reduction in the cumulative forest carbon sequestration between year 2006 – 2099 by 15%. Goll et al. (2012) showed that carbon sequestration during the 21st century in the JSBACH land surface model was 25% lower when N and P effects were considered.

Mineral weathering is a natural and primary source of geogenic nutrients (Hopkins and Hüner, 2008;Landeweert et al., 2001), and controls atmospheric CO_2 concentrations over geological timescales (Walker et al., 1981;Lenton and Britton, 2006;Berner and Garrels, 1983). Chemical dissolution of silicate minerals increases alkalinity fluxes (Kempe, 1979;Gaillardet et al.,

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1999;Hartmann et al., 2009), and natural weathering sequesters up to 0.3 Gt C a^{-1} (Gaillardet et al., 1999). To sequester significant amounts of CO_2 within decades, EW aims to speed up weathering processes by increasing the weatherable mineral surfaces through rock comminution (Hartmann et al., 2013;Schuiling and Krijgsman, 2006;Hartmann and Kempe, 2008). Mineral-soil-microorganism interactions, *e.g.*, by mycorrhizal fungi (Kantola et al., 2017;Landeweert et al., 2001;Taylor et al., 2009) increase the volume of soil that plant roots can extract nutrients from (Clarkson and Hanson, 1980;Hopkins and Hüner, 2008), which might enhance the weathering activity in addition to the reaction with dissolved CO_2. EW further increase soil pH by alkalinity fluxes, and could be a long-term source of macro- (*e.g.*, Mg, Ca, K, P, and S), and micronutrients (*e.g.*, B, Mo, Cu, Fe, Mn, Zn, Ni) (Leonardos et al., 1987;Nkouathio et al., 2008;Beerling et al., 2018;Hartmann et al., 2013;Anda et al., 2015) rejuvenating the nutrient pools of soils.

P is rather immobile soil nutrient and only a small fraction of soil P is readily available for plant uptake limiting plant growth in a wide range of ecosystem (Shen et al., 2011;Elser et al., 2007). Orthophosphate ($H_2PO_4^-$ or HPO_4^{2-}) is the chemical species adsorbed by plants (Shen et al., 2011) and its solubility is controlled by soil pH as de-protonation occurs when pH increases. Ideal pH conditions for orthophosphate availability are from 5 to 8 (Holtan et al., 1988). Soil P availability seems to be influenced by soil moisture for different crops (He et al., 2005;He et al., 2002;Shen et al., 2011), and natural ecosystems (Goll et al., 2018).

The inclusion of soil hydraulic properties in the evaluation of EW effects is important as the soil water content has a strong influence on average crop yield. Practices that increase the plant available water (PAW) are thought to mitigate drought effects on crops (Rossato et al., 2017). The water content of soils also seems to influence soil erosion rates and surface runoff (Bissonnais and Singer, 1992). In addition, soil water content influences soil pCO_2 production, which is a relevant agent for mineral dissolution (Romero-Mujalli et al., 2018).

Deploying land-based NETs would imply large changes in a local landscape nutrient and water cycles. At least 65% of worldwide soils (6.8 billion hectares of land) have unfavorable soil conditions for biomass production (Fischer et al., 2001). Therefore, we assess if applications of rock mineral based P sources could close eventual nutritional gaps in an environment with natural N supply (N-limited) and with N fertilization (N-unlimited), using a global afforestation scenario. In addition, we investigate the effects of coupling nutrient supplying (EW) to nutrient demanding (AR and BG) land-based NETs by focusing on the efficiency of different upper limits of basalt powder to supply nutrients. We hypothesize that large-scale EW deployment potentially changes soil texture. Therefore, threshold values for impacts on soil hydraulic conductivity, and plant available water will be determined.

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2. Methods

Since phosphorus (P) is a limiting nutrient in a wide range of ecosystems (Elser et al., 2007), we performed a P budget for an N stock-based P demand from an AR scenario considering natural N supply (hereafter N-limited) and N fertilization (hereafter N-unlimited). We chose two N supply scenarios since the related P demand is proportional to biomass N stock, but in the main text we discuss the N-limited AR scenario. Based on ideal Mg, Ca, and K demand of AR derived from databases of biomass Mg, Ca, and K content, we estimated the balanced supply of these nutrients for each supplied P to avoid shift of growth limitation to other nutrients (von Liebig and Playfair, 1843). Based on minimum and maximum harvest rates of bio-energy grass (BG), we estimated the related exported P and K by harvest from the fields. We choose these nutrients for BG since crops require large amounts of K and P. The amount of rock powder for Enhanced Weathering (EW) to cover projected P gaps and to replenish exported nutrients was estimated. The projected impacts on soil hydrology due to EW deployment were done by pedotransfer functions since they are used to estimate soil hydraulic properties (Schaap et al., 2001;Whitfield and Reid, 2013;Wösten et al., 2001) and such approximations have proven to be a suitable approach (Vienken and Dietrich, 2011).

The additional AR P demand, obtained for the 21st century for an N-unlimited and N-limited AR scenario (Kracher, 2017) was approximated by stoichiometric P:N ratios for mean and range (5th and 95th percentiles), which is a similar approach done by Sun et al. (2017). The ratios were derived from databases of hard- and softwood (Pardo et al., 2005) and foliar biome-specific nutrient content (Vergutz et al., 2012). We then compared the inferred P demand to geogenic P supply given by observation-based estimates of soil inorganic labile P and organic P (Yang et al., 2014a), observation-based estimates of P release (Hartmann et al., 2014) from weathering corrected to future temperature increase (Goll et al., 2014) and estimated atmospheric P depositions from Wang et al. (2017) to derive the potential geogenic P deficits, *i.e*, the P gap, during the 21st century. Since the geogenic P supply cannot cope with N stock-based P demand from the different AR scenarios within P gapped areas, the biomass production and biomass C sequestration, predicted by the AR scenarios, will be lower. Based on the amount of missing P, we estimated the C-stock reduction within P gapped areas by using stoichiometric C:P ratios. The C:P ratios were derived from simulated C stock content (Kracher, 2017) and inferred N stock-based P demand.

Necessary Mg, Ca, and K supply for balanced tree nutrition based on P supply were derived from N stock-based Mg, Ca, and K additional demand normalized to the N stock-based additional P demand (Fig. 1). The nutrient demand of bio-energy grass was estimated based on stoichiometric P:N and K:N ratios, used in Bodirsky et al. (2012), for minimum and maximum exported N proportional to harvest rates of the 1995 – 2090 period obtained from the agricultural production model MAgPIE (Fig. 1). Later on, the necessary amount of rock to cover the P gaps of AR scenario and to resupply the exported nutrients by BG harvest was estimated (Fig. 1). In addition, the potential impact of deploying rock powder into the topsoil was done. Detailed description on used data and assumptions are given below.

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2.1. Global land-system model output

2.1.1. Afforestation/Reforestation

The idealized simulations for the AR system from Kracher (2017) performed by the land surface model JSBACH (Reick et al., 2013) for a representative greenhouse concentration pathway 4.5 (RCP4.5) were used (Thomson et al., 2011). The JSBACH simulations assume N-unlimited and N-limited conditions, and consider harvest rates, and transitions between different anthropogenic and natural land cover types (Hurtt et al., 2011) for a Gaussian grid of approximately 2°×2° resolution. The net primary productivity (NPP) calculation was based on atmospheric CO_2 concentrations, stomatal conductance, and water availability. JSBACH considers mass conservation, a supply-demand ansatz, and fixed C:N ratios (Goll et al., 2012). Kracher (2017), considered forest regrowth on abandoned croplands, which in the long term become acidic and consequently favor leaching of nutrients and heavy metals (Hesterberg, 1993), natural shift in natural vegetation, and future CO_2 increase leading to CO_2 fertilization.

We retrieved the annual changes in N and C content of different pools, *i.e.*, Wood (above and below ground, also including litter) and foliar (above and below ground, also including litter) for temperate, cold, tropical, and subtropical climate growing forests and shrubs plant functional types for years 2006 – 2099 and annual model output.

2.1.2. Biomass production from bio-energy grass

Simulations of BG nutritional needs from the agricultural production model MAgPIE, a framework for modeling global land-systems (Dietrich et al., 2018;Lotze-Campen et al., 2008;Popp et al., 2010) were used. The objective of MAgPIE is to minimize total costs of production for a given amount of regional food, bio-energy demand and climate target (here RCP4.5). In its biophysical core, the yields in the model are based on LPJmL (Bondeau et al., 2007;Beringer et al., 2011;Müller and Robertson, 2013), a dynamic global vegetation model, which is designed to simulate vegetation composition and distribution for both natural and agricultural ecosystems.

At the starting point of the simulation, the LPJmL bio-energy grass yields have been scaled using agricultural land-use intensity levels (Dietrich et al., 2012) for different world regions accounting for the yield gap between potential and observed yields for the period 1995 – 2005. For the future yields (2005 – 2090), the development is then driven by investments into yield-increasing technologies (Dietrich et al., 2014) based on the socio-economic boundary conditions of the system.

The MAgPIE output had a frequency of 10 years and the global minimum, and maximum of each output year was taken to obtain the potential bio-energy grass minimum and maximum harvest rate for the simulation period, which is 0.7 and 3.6 kg m^{-2} a^{-1}.

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2.2. Nutrient demand

2.2.1. Afforestation/Reforestation

The P, Mg, Ca, and K additional demand is defined as the amount of P, Mg, Ca, and K needed to realize the state of ecosystem N variables in each grid cell and year according to JSBACH output (Fig. 1). It was estimated from the spatially explicit information on average forest N content of each stock and plant functional type for an N-unlimited, and an N-limited AR scenario from Kracher (2017). Since P limits forest growth in a wide range of ecosystems (Elser et al., 2007), we performed a P budget for each AR scenario. The ideal P, Mg, Ca, and K biomass additional demand were based on the difference in the simulated change in N pools at that time with respect to the simulation year of 2006 multiplied by their corresponding Mg:N, Ca:N, K:N, or P:N ratios (r_{ij}) and were calculated following Eq. (1):

$$\Delta M_{pool,i} = \sum_{j=1}^{n} \Delta N_{ij} \times r_{ij}, \quad (1)$$

where $\Delta M_{pool,i}$ [kg m^{-2} a^{-1}] is the average N stock-based Mg, Ca, K, or P demand for a given time in the future simulation time range (2007 – 2099) within a cell for biome i. ΔN_{ij} [kg m^{-2} a^{-1}] is the average N stock change of pool j. n is the number of N pools. The N pools considered are: Wood (above and below ground, including litter) and foliar (above and below ground, including litter).

The P, Mg, Ca, K, and N content of leaves obtained from a global leaf chemistry database (Vergutz et al., 2012) was used to derive the Mg:N, Ca:N, K:N, or P:N ratios (Table 1), which was already biome classified. For wood, the tree chemical composition database of US forests (Pardo et al., 2005) was used in order to derive the global ratios, which were assumed to represent the chemical composition of all biomes (Table 1).

The AR C content from Kracher (2017) and the resulting N stock-based Mg, Ca, and K demand were normalized by the N stock-based P demand to estimate the mean and range C:P, Mg:P, Ca:P, and K:P ratios of each grid cell. The stoichiometric C:P, Mg:P, Ca:P, and K:P ratios were used to derive the C-fixation reduction due to P deficiencies and the necessary Mg, Ca, and K supply for a balanced biomass nutrition based on supplied P (Fig. 1).

2.2.2. Biomass production from bio-energy grass

The BG yield was obtained by the spatially explicit harvest rates within a grid cell for an output frequency of 10 years and a period of 95 years (1995 – 2090).The minimum 0.7 kg m^{-2} a^{-1} and maximum 3.6 kg m^{-2} a^{-1} harvest rate were used. With the information on exported N by each harvest rate the exported K or P from cultivation fields (eq. 2) were estimated based on the P:N, and K:N stoichiometric ratios used in Bodirsky et al. (2012). We have chosen these nutrients, since crops require large amounts of K and P.

Differently from the AR scenario forests, which are perennial, bio-energy grasses are harvested regularly due to their use as biomass feedstock for BECCS. Thus, the natural system's nutrient supply is insufficient to maintain successive and constant

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yields, and the exported nutrients by harvest need to be replenished (Cadoux et al., 2012) to maintain high yields. The exported nutrient was calculated following Eq. (2):

$$Bio_x = r_x \times N_{harvest}, \qquad (2)$$

where Bio_x corresponds to the exported nutrient P or K [kg m^{-2} a^{-1}] by harvest. r_x is the P:N or K:N stoichiometric ratio used in Bodirsky et al. (2012). $N_{harvest}$ is the exported N for a minimum 0.7 kg m^{-2} a^{-1} or a maximum 3.6 kg m^{-2} a^{-1} harvest rate. The harvest rate value was based on the MAgPIE output for each grid cell, representing the minimum and maximum projected global harvest rate for a period of 95 years.

2.3. Geogenic P supply for AR

Since the geogenic P source databases have different spatial resolution (Table 2), we resampled each of them to 2°×2° spatial resolution fields by nearest neighbor interpolation. As the uncertainty on which P pool is available for long-term plant nutrition is high (Johnson et al., 2003), two scenarios for soil P supply were investigated: scenario one considering P from weathering and atmospheric P deposition. Scenario two the same as scenario one plus inorganic labile P and organic P (Yang et al., 2014a)(Supplement S1 Fig. S2).

The total P supply by weathering for the 21th century (2006 – 2099) was based on Hartmann et al. (2014) maps (Supplement S1 Fig. S3). A relationship between air temperature and weathering rate was used, whereby P weathering increases by 9% per 1ºC increase (Goll et al., 2014) without accounting for P concentration changes in primary and secondary P minerals.

The atmospheric dry and wet P deposition rates were taken from simulation outputs for the 2006 – 2013 period and for the years 2030, 2050, and 2099 for an RCP4.5 scenario (Wang et al., 2017). The simulations were based on P emissions of sea salt, dust, biogenic aerosol particles, and P emitted by combustion processes, and performed by the global aerosol chemistry-climate model LMDZ-INCA, *cf.*, Wang et al. (2017) for a detailed description of model and model assumptions. The simulation gaps were closed by linear regression and the cumulative atmospheric P deposition (Supplement S1 Fig. S1) was calculated by summing up the deposition rate of each cell for 2006 – 2099 period according to Eq. (3):

$$P_{tot} = \sum_{i=2006}^{2099} P_i, \qquad (3)$$

where P_{tot} [kg m^{-2}] is the cumulative atmospheric P deposition of the 2006 – 2099 period. P [kg m^{-2} a^{-1}] is the atmospheric P deposition of each year i within a grid cell.

2.4. Estimating geogenic P gap, related C-fixation reduction, and balanced Mg, Ca, and K supply for AR

The potential P gap (P_{gap} [kg m^{-2}]) was estimated as the difference between additional mean and range (95th and 5th percentiles) P demand estimated from the N stock for the two different AR scenarios (section on Afforestation/Reforestation nutrient

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demand), and the geogenic P supply from the different supply scenarios (P_{sup} [kg m^{-2}]) within the cover fraction for a grid cell of biome i (f_i [-]), for 21st century (2006 – 2099) according to Eq. (4):

$$P_{gapt} = P_{sup} \times f_i - \Delta P_{pool,i}, \tag{4}$$

the plant C-fixation reduction was estimated based on the P gap and calculated following Eq. (5):

$$C = r_C \times P_{gapt}, \tag{5}$$

where C [kg m^{-2}] is the plant reduced C-fixation due to the projected P gap. r_C is the used stoichiometric C:P ratio based on mean and range (5th and 95th percentiles) chemistry for wood and leaves derived from the N-limited and N-unlimited AR scenario N stock as described in subsection 2.2.1.

The Mg, Ca, and K necessary supply for balanced biomass nutrition (M_x [kg m^{-2}]) should be proportional to the supplied P (P_{EW} [kg m^{-2}]) and was calculated following Eq. (6):

$$M_x = r_x \times P_{EW}, \tag{6}$$

with P_{EW} being equal to the projected P_{gap} since the P_{gap} is covered by P from Enhanced Weathering according to Eq. (7):

$$P_{EW} = P_{gap}, \tag{7}$$

where r_x is the used stoichiometric ratio Mg:P, Ca:P, K:P obtained by normalizing the N stock based additional Mg, Ca, and K demand to the N stock based additional P demand.

2.5. Enhanced Weathering Mg, K, Ca, and P potential supply

To cover the potential of different igneous rocks for EW strategies, rhyolite and dacite (acid rocks), andesite (intermediate rock) and basalt (basic rock) were chosen to project used masses to cover P gap from the AR scenarios. For this, data collection of macronutrient concentrations (Mg, Ca, K, P) in weight percent within these rocks were done (Supplement S1 Fig. S4) (Earthchem web portal, http://www.earthchem.org, accessed on 2017-07-14).

The nutrient supply was estimated assuming complete rock powder dissolution in the system, which is expected over long timescales depending on the grain size (*i.e.*, one year for grain sizes between 0.6 – 90 µm (Strefler et al., 2018)). The results and discussion will focus on basalt rock powder considering median values and range (5th and 95th percentiles), as basalt is abundant worldwide (Amiotte Suchet et al., 2003;Börker et al., 2018) and has a high P content. Other rock types are included, but the results are provided in the supplementary text (Supplement S1 section S4). The necessary mass of rock powder to supply macronutrient (Mg, Ca, K, or P) was calculated following Eq. (8):

$$R_d = \frac{M_{ex}}{f_{nut}}, \tag{8}$$

where R_d [kg rock m^{-2} or kg rock m^{-2} a^{-1}] represents the mass of a rock type to cover AR or BG nutritional needs, M_{ex} [kg m^{-2} or kg m^{-2} a^{-1}] is the mass of required nutrient for AR or BG, *e.g.*, P to cover a P gap, and f_{nut} [-] is the median and range (5th or 95th percentile) fractions of interest nutrient within the chosen rock, *i.e*, for P in basalt a median of 500 ppm and ranges of 157 ppm for 5th percentile and 1833 ppm for 95th percentile is expected.

230 However, the potential nutrient supply by EW for different amounts of rock powder being deployed was also estimated following Eq. (9):

$$Nut_{in} = M_{rock} \times f_{nut}, \tag{9}$$

where Nut_{in} [kg m^{-2} or kg m^{-2} a^{-1}] represents the macronutrient input by dissolving a chosen rock. M_{rock} [kg rock m^{-2} or kg rock m^{-2} a^{-1}] is the mass of rock added to the natural system.

2.6. Related impacts on soil hydrology from Enhanced Weathering deployment

235 Large scale deployment of rock powder on soils is expected to influence soil's texture. The deployed amount and texture of rock powder will affect hydraulic conductivity, water retention capacity, and specific soil surface area. Pedotransfer functions (PTFs) are used to estimate soil hydraulic properties (Schaap et al., 2001;Whitfield and Reid, 2013;Wösten et al., 2001) based on statistical analysis (Saxton and Rawls, 2006;Wösten et al., 2001), artificial neural networks, and or other methods applied to large soil databases of measured data (Wösten et al., 2001).

240 The impacts of basalt powder application on soil hydrology are estimated for soils corresponding to P gap areas from the N-unlimited AR scenario as a function of rock powder deployment by the use of PTFs from Saxton and Rawls (2006) (Supplement S1 section S5). The N-unlimited AR scenario was chosen since this scenario would have the highest P deficiencies requiring more rock powder to cover the P gaps. The estimations are for a homogeneous mixture of rock powder and topsoil depth of 0.3 m. Downward transport of fine-grained material is neglected for simplification. The considered values represent 245 upper limits of rock powder application. The impacts on plant available water (PAW) is given by the difference between water content at a pressure head of -33 kPa (Supplement S1 eq. (S7)) and -1500 kPa (Supplement S1 section S5 eq. (S6)) (Saxton and Rawls, 2006), while the impact on soil hydraulic conductivity is given by Eq. (10):

$$K_S = 1930 \times (\theta_S - \theta_{33})^{(3-\lambda)}, \tag{10}$$

where K_S [mm h^{-1}] represents the saturated soil hydraulic conductivity, θ_{33} represents the soil moisture for a pressure head of -33 kPa ($R^2 = 0.63$; Supplement S1 section S5), θ_S corresponds to the saturated (0 kPa) moisture ($R^2 < 0.25$; Supplement S1 250 section S5), and λ is the slope of logarithmic tension-moisture curve (Supplement S1 section S5) (Saxton and Rawls, 2006).

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3. Results and discussion

3.1. Enhanced Weathering coupled to Afforestation/Reforestation

Phosphorus (P) is a limiting nutrient in a wide range of ecosystems (Elser et al., 2007). P deficiency might affect biomass growth of tropical (Herbert and Fownes, 1995;Tanner et al., 1998;Wright et al., 2011) and northern forests (Menge et al., 2012;Shinjini et al., 2018). The numerical simulations of Kracher (2017) predict biomass growth for the 21st century (Supplement S1 Fig. S5) considering natural water supply, CO_2 fertilization, and N-unlimited and N-limited scenario. In the present text, we will focus on the results from the N-limited scenario since it considers natural N supply. In the supplement, the results for the N-unlimited scenario are presented. The predicted C sequestration by the N-limited AR scenarios from Kracher (2017) is 2.0 Gt C a^{-1}. Different authors reported the potential C sequestration by afforestation or reforestation being of 0.3 – 3.3 Gt C a^{-1} for the end of 2099 (National Research Council, 2015;Lenton, 2014, 2010;Smith et al., 2015 apud Fuss et al., 2018).

The here estimated P demand based on the predicted biomass growth to sequester 190 Gt C (N-limited AR scenario) amounts to 200 Mt P on global scale for a mean wood and leaves P content. Since there are more than 60,000 tree species recorded worldwide (Beech et al., 2017) a precise estimation on tree chemistry represents a challenge. Based on global and US specific databases, the range of N stock-based additional P demand is 71 / 345 Mt P; 5th / 95th percentile for wood and leaves chemistry. The P budget for geogenic P supply scenario one, with P supply by weathering and atmospheric deposition, suggest that P deficiency areas are distributed around the world, but with more frequent occurrences in the northern hemisphere (Fig. 2a). However, for geogenic P supply scenario two, which is the same as geogenic P supply scenario one plus geogenic P from soil inorganic labile P and organic P pools, the P deficiency areas are predominantly located in the southern hemisphere (Fig. 2b). If N and P are limiting nutrients, it is expected a C reduction of 16.5 – 59.0%, with mean C reduction of 47.0% for the geogenic P supply scenario one and 19.0% for the geogenic P supply scenario two. Therefore, accounting for N and P limitation on AR suggests that, in average; the biomass production will be more affected, which decreases the C sequestration potential of AR strategies (Table 3). In some areas, the C sequestration can be reduced by up to 100% compared to the predicted C sequestration of the AR models (Fig. 3).

Different pathways and mechanisms control soil P availability to the plant (Vitousek et al., 2010), and they are not considered in our estimations leading to conservative predictions. Adding soil P dynamics to models would allow to reliably quantify the C sequestration potential of AR, *e.g.,* using P enabled land surface models (Sun et al., 2017;Wang et al., 2017;Goll et al., 2012;Goll et al., 2017;Wang et al., 2010;Yang et al., 2014b).

Kracher (2017) has shown that N can limit biomass production and consequently C sequestration. To achieve the projected C sequestration of 190 Gt C for N-limited scenario, the estimated P gaps must be closed. Potential P sources are industrial fertilizers, like diammonium phosphate (DAP) or rock powder, *e.g.,* basalt. However, DAP potentially represents an extra

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input of ammonium to the groundwater and it is expected, in the long-term, that DAP deployment acidifies the soil (Fertilizer Technology Research Centre).

Most of the world soils are acidic, with some being strongly acidic (IGBP-DIS, 1998), which generally favors the sorption of orthophosphate onto Fe- and Al-(hydro)oxides surfaces and clay minerals, essentially demobilizing P (Shen et al., 2011). Besides that, the long AR time span can undermine the effectiveness of DAP to supply P for forests due to the high soil acidification potential of DAP. Therefore, rock powder application can be an alternative as nutrients are slowly released and an increase of alkalinity fluxes is expected (Dietzen et al., 2018), which can raise and stabilize the pH of soils.

Correcting soil pH to ideal conditions, generally between 6.6 and 7, will provide new nutrient holding sites at Fe- and Al-(hydro)oxides surfaces, and at soil organic matter and the sorbed orthophosphate will be plant available. An application of 8 kg m^{-2} basalt powder can increase the CEC of oxisols by 150 – 300% (Anda et al., 2015;Anda et al., 2009) and improve the C- and N-mineralization (Mersi et al., 1992).

Assuming a median P content of 500 ppm in basalt, *cf.*, subchapter 2.5, the maximum mass applied in 94 years would be of 33 and 13 kg basalt m^{-2} respectively for P gap from both geogenic P supply scenarios. Considering the basalt deployment areas, a total amount of 2 – 362 Gt basalt applied by EW would be needed to cover the projected P gaps (5^{th} – 95^{th} percentile from geogenic P supply scenario two and one). Basalt has a carbon capture potential of ~0.3 tCO_2 t^{-1} basalt (Renforth, 2012), sequestering 0.6 – 97.8 Gt CO_2 by the end of 2099 if basalt powder would be deployed to cover P gaps of the N-limited AR scenario.

Rhyolite, dacite or andesite could alternatively be used as a source of P, but these rocks generally have lower P content than basalt. As a consequence, the necessary amounts of each rock to cover P gap of each P budget scenario for the AR scenarios, based on chemical composition, will be higher. Therefore, basalt powder is more effective to supply P for the estimated P gap areas due to relative high P content.

To avoid shifts of nutrient limitation, the supply of macronutrients like Mg, Ca, and K should be proportional to P supply since Mg is required as an essential element in chlorophyll, Ca has a structural role, and K is responsible for water and ionic balance (Hopkins and Hüner, 2008). Rock powder can be used as source of these nutrients, as suggested by different authors (Beerling et al., 2018;Hartmann et al., 2013;Straaten, 2007). Therefore, we investigated if these macronutrients are supplied by EW for balanced tree nutrition. Assuming median rock nutrient content, the different rock types under study can supply the necessary amount of Ca, Mg, and K for balanced tree nutrition if they are used to close the projected P gaps (Supplement S1 Fig. S6). The potential of basalt powder to supply K, based on chemical composition, is lower than for other analyzed rocks. For median values, rhyolite has the highest content of K; however, if occurring in K-feldspars it will not be plant available. Blending these rocks in different proportions could result in a more balanced macronutrient supply (Leonardos et al., 1987).

For a rock chemical composition corresponding to the 95^{th} percentile of P content, 10 kg basalt m^{-2} would cover the maximum projected P gaps for all P supply scenarios. For a median chemical composition of rock, deploying 33 kg basalt m^{-2} would cover all the P gaps of the two geogenic P supply scenarios. For the 5^{th} percentile, the necessary amount of rock would be even higher. Besides successfully covering the estimated P deficiencies, basalt powder seems to supply enough K, Mg, and Ca to the afforested system contributing to balanced biomass nutrition (Fig. 4) and, as expected, avoiding shift of growth limitation to other nutrients.

3.2. Enhanced Weathering coupled to biomass production from bio-energy grass

Generally, natural soil P content is inadequate for long-term cultivation of agricultural plants. To overcome this issue, P is supplied by fertilizers to reach or maintain optimum levels of crop productivity (Sharpley, 2000) after several harvest rotations. In order to keep a positive CO_2 balance, an alternative to industrial fertilizers should be used to replenish the exported nutrients by harvest. Rock powder application could increase the soil macro- and micronutrient stocks, maintaining or increasing biomass yields without decreasing CDR efficiency. For a high nutrient content (95% confidence intervals) deploying up to 1.5 kg basalt m^{-2} a^{-1} could meet the K needs of bio-energy grass (Fig. 5) and would be able to replenish up to 75% of the exported P, if the maximum bio-energy grass yield is considered (Fig. 5). Industrial fertilizer co-application would be indicated to completely replenish exported P reducing industrial fertilizers dependency. Deploying 8 kg basalt m^{-2} a^{-1} would be enough to replenish exported K and P by harvest assuming median nutrient content of basalt powder (Fig. 5).

The chemical composition of rocks is highly variable (Supplement S1 Fig. S4). Different rock types can be used for EW and ideal rock types need to be chosen in order to resolve a specific plant nutrient deficiency, and enhance the nutrient reservoir of a target soil besides increasing the soil pH, the CEC (Anda et al., 2015;Anda et al., 2009), improve the C- and N-mineralization (Mersi et al., 1992), the soil organic carbon (Doetterl et al., 2018) and the supply of Si (Beerling et al., 2018;Hartmann et al., 2013). In the case of oxisols, application of 8 kg m^{-2} basalt powder can increase the CEC by 150 – 300% (Anda et al., 2015;Anda et al., 2009).

Overall, rock application could resupply the harvest exported nutrients, and close the short- and long-term nutrient gaps in soil. Individual rock types, from basic (Mg, Ca) to acidic (K, Na), contain varying amounts of target nutrients and mixing them might increase the overall nutrient supply capacity (Leonardos et al., 1987). Intrinsic mineralogical and or petrographic structures can influence the release of nutrients (Ciceri et al., 2017), which makes them plant unavailable in some cases. K can also limit plant growth; it occurs in K-feldspars as a plant unavailable form, in the case of acid rocks, but becomes accessible after hydrothermal treatment (Liu et al., 2015;Ma et al., 2016a;Ma et al., 2016b). However, research on release processes of other macro- and micronutrients and on nutrient-release optimization, *e.g.*, by hydrothermal decomposition, is necessary to be able to parameterize this effect in the soil environment.

3.3. Impacts on soil hydrology

AR and BECCS demand huge quantities of irrigation water (Boysen et al., 2017b;Bonsch et al., 2016), and it is projected that climate change will affect the water balance, and consequently influence crop yields (Kang et al., 2009). Soils with higher

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water holding capacity will better tolerate the impacts of drought (Kang et al., 2009). Therefore, practices that improve water availability to plants at the root system are used as strategies to mitigate drought effects (Rossato et al., 2017). We investigated if deployment of rock powder can change the top soil hydraulic conductivity, and plant available water (PAW) for different application ranges.

To show baseline hydraulic properties for soils with any sort of P gap, the initial hydraulic properties were estimated, and they show high variability. The projected hydraulic conductivity (K_S) of top soils for areas corresponding to those of P budget from geogenic P supply scenario one (Supplement S1 Fig. S21a), for the N-unlimited AR scenario encompass values ranging from 1.5×10^{-7} and 7.8×10^{-4} m s^{-1} and for PAW of 4% and 32% (Table 4). Neglecting the topography, soils having low K_S, *e.g.*, values of 1.5×10^{-7} m s^{-1}, would experience the lowest water infiltration rate. The impacts of deploying a fine basalt texture (15.6% clay, 83.8% silt, and 0.6% fine sand) or a coarse basalt texture (15.6% clay, 53.8% silt, and 30.6% fine sand), which are in the range of commercial powders (Nunes et al., 2014), on soil hydrology were estimated for different application upper limits.

Impact of rock-powder deployment could be neglected, in average, for upper limits until 50 and 205 kg basalt m^{-2} respectively for a fine and a coarse textured rock powder being deployed. However, deviations from what is expected for the mean might occur (Fig. 6 and Supplement S1 Fig. S23 for P gap from geogenic P supply scenario two). The average values for PAW increase together with the increase of the upper limits of rock powder application, but for a coarse basalt powder some areas might experience a decrease in the PAW (Fig. 6 and Supplement S1 Fig. S23 for P gap from geogenic P supply scenario two). However, overloading the soil system with rock powder can trigger plant suffocation, if gas exchange is prevented by water saturation of pores (Sairam, 2011).

Closing the observed P gap from areas presented in Supplement S1 Fig. S21 would require a maximum deployment of 34 kg basalt m^{-2} for P budget of geogenic P supply scenario one and 13 kg basalt m^{-2} for P budget of geogenic P supply scenario two (Supplement S1 Fig. S7). The P gaps from scenario two (Supplement S1 Fig. S21b) could be filled by a coarse or fine basalt powder and the related changes in soil hydrology could be neglected, remaining below 10% (for more or less) for most of the areas (Supplement S1 Fig. S26 and S27). If the geogenic P supply from scenario one, for the N-unlimited AR scenario (Supplement S1 Fig. S21a) is assumed and a fine basalt powder is applied, the maximum and minimum changes on hydraulic conductivity could be of 58% and -11.0% (Supplement S1 Fig. S24a). Decrease on PAW could be neglected for most of the deployment areas, but some would have an increase of up to 31.0% from 13.8% to 18.2% (Supplement S1 Fig. S24b). A coarse basalt powder would, in general, cause fewer impacts to soil hydraulic properties (Supplement S1 Fig. S25).

Concrete effects of EW on biomass productivity would depend if the changes in the initial PAW values for top soils would reach PAW threshold values to trigger biomass productivity (Sadras and Milroy, 1996). In general, the average changes on topsoil PAW related to basalt powder application would not be enough to trigger biomass growth, *e.g.*, areas showing PAW changes from 14% to 21% would not trigger leaf and stem expansion of maize, wheat or soybean, but could increase leaf and

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stem expansion of pearl millet after deploying 50 kg basalt m^{-2} with a fine texture. 50 kg basalt m^{-2} of coarse powder changes PAW by 19% consequently not triggering biomass productivity.

The equations from Saxton and Rawls (2006) do not consider changes in the rock powder mineralogy, *e.g.*, by clay mineral formation, which can potentially increase the water holding capacity of soils, and subsequently change the PAW. The suitable amounts of rock powder applied depend on the target changes of the chosen soil, and on its intrinsic grain size distribution and organic matter content. Intrinsic grain properties like the shape of grains and pores, tortuosity, specific surface area, and porosity should be considered (Bear, 1972). Field and laboratory experiments would enable a qualitatively, and quantitatively reliable assessment of soil hydrology impacts. The impacts on soil microorganisms should be taken into account in order to correct the limits of rock powder deployment.

3.4. Challenges of rock powder deployment

Average tillage depth common machinery can reach is 0.3 m and greater depths cause higher energy, and labor costs (Fageria and Baligar, 2008). Since annual crops have an effective rooting depth typically in the range of 0.4 – 0.7 m (Madsen, 1985;Aslyng, 1976;Munkholm et al., 2003;Olsen, 1958), deployment depths of 0.3 m seems to be reasonable.

Once tillage can trigger soil carbon loss (Reicosky, 1997;La Scala et al., 2006), deploying rock powder at soil surface might be a solution. At the soil surface, the long-term water percolation, and or bioturbation (Fishkis et al., 2010;Taylor et al., 2015) can transport and mix fine-grained material to deeper regions within the soil profile, which potentially can change the K_S, and PAW at crop rooting zones. Groundwater recharge rates might change if clogging of pores at deeper regions of soil profile occurs. Taylor et al. (2015) argue that downward transport of a silt-textured powder deployed at soil surface would easily reach the rooting zone of trees, which is in its majority in a depth up to 0.4 m. The authors suggest that in tropical regions higher depths might be reached due to intensive rain and bioturbation.

Detailed field studies to better comprehend downward transport of grained material through the soil profile, changes on soil water residence time, PAW, mineralogy, nutrient pools, CEC (Anda et al., 2015, 2013), and bioavailability of released trace metals (Renforth et al., 2015) are necessary, to be able to provide management recommendations for the diverse existing settings for EW application. In the present study, estimates for different basalt powder application upper limits are done for changes in soil hydraulic properties without accounting for downward transport of fine particles through the soil profile.

Besides avoiding clogging of pores of the top soil layer by rock powder application in a certain extent, downward transport of rock powder can contribute freshly ground material being in contact with roots of trees or crops, which can enhance the weathering rates and create new sites to retain nutrients (Kantola et al., 2017;Anda et al., 2015).

Once the freshly ground material is in contact with the soil, different factors control the nutrient supply efficiency of rock powder. The nutrients from fresh material are initially inert protected within the crystallographic structures of the minerals, and would become plant-available only in solution or associated to mineral surfaces (Appelo and Postma, 2005). The release

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of nutrients by weathering is controlled by film and intra-particle diffusion-limited mass transfer influenced by pH, and ionic strength of the soil aqueous solution (Grathwohl, 2014), both being controlled by rooting exudates in the rhizosphere and chemical composition of infiltrating waters.

Under field conditions, soil water could rapidly reach near-equilibrium concentrations (Grathwohl, 2014), which would decrease weathering rates. The opposite would occur if near-equilibrium conditions could be disturbed by a sink of nutrients by nutrient root uptake (Stefánsson et al., 2001) or by percolation of water un-equilibrated with soil porous water (Calabrese et al., 2017).

Besides the potential to be used to rejuvenate soil nutrient pools (Leonardos et al., 1987), silicate rock powder can be used to reduce the risk of nitrate mobilization, being indicated for regions in which special care to water preservation is needed. However, extra input of sodium (Na) to the system, if the rock is rich in this element, could disturb this amelioration effect (Von Wilpert and Lukes, 2003). Besides decreasing nitrate mobilization, co-application of rock powder with other fertilizers can increase the biomass production of crops (Anda et al., 2013;Leonardos et al., 1987;Theodoro et al., 2013).

4. Conclusions

Our results illustrate the potential of Enhanced Weathering (EW) to act as a nutrient source to nutrient demanding AR and BG. This is an important, yet overlooked, aspect of EW besides CO_2 sequestration. The investigated scenarios show that areas with undersupply of P exist, and a C-stock reduction is expected to occur if P is the only limiting nutrient. Considering N, and P deficiency together, the C-stock reduction increases up to 59% of the projected total global C sequestration potential of 224 Gt C. Potential P deficiencies were here based on the soil P availability and P demand scenarios, indicating that the inclusion of P cycles in AR models is necessary to accurately project the C sequestration of forests. Industrial fertilizers can be used to alleviate the P deficiency but the extra input of ammonium along with it can undermine the carbon budget and acidify the soils. Furthermore, acidic soil conditions generally favors the sorption of orthophosphate onto Fe- and Al-(hydro)oxides surfaces and clay minerals, essentially demobilizing P (Shen et al., 2011).

Besides the high chemical P content and relative fast weathering rates, the equilibrated supply of Ca, K, and Mg put the use of basalt powder one step ahead as a potential alternative to industrial fertilizers. Regrowth of forests on abandoned agricultural land is a passive landscape restoration method (Bowen et al., 2007). In most of the cases soils become acidic in abandoned agricultural land in the long term (Hesterberg, 1993), which favors the leaching of nutrients (Haynes and Swift, 1986) and heavy metals (Hesterberg, 1993). As a consequence, the regrowth rate of forests might be limited in acidic soils. The use of basalt powder will keep a positive carbon budget, increase the soil pH (Anda et al., 2015;Anda et al., 2009), as basalt powder would act as a buffer maintaining soil pH under neutral to slight alkaline conditions, close nutritional needs of AR and BG, and rock powder can be used to reduce the risk of nitrate mobilization (Von Wilpert and Lukes, 2003). However, to be able to assess the global potential of the combination of land-based biomass NETs with EW; it is necessary to compile knowledge on

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the related physico-chemical changes of soil influenced by a variety of EW deployment rates, from the already available data, and then develop improved EW models. They should be tested with field-based approaches. For example, tracking added elements through the ecosystem's soil and plant reservoirs probably needs test sites using advanced methods of nutrient balance and isotope studies, as recently developed (Uhlig, 2019).

In addition to the use for replenishing soil nutrient content, our research suggests that deployment of rock powder on the top soil can enhance Plant Available Water (PAW) for different upper limits. Apart from controlling the nutrient release rates, the texture of deployed rock powder would influence the impacts on soil hydrology together with the initial soil texture. In general, EW appears to have considerable potential for water retention management of top soils. This is an important characteristic not explored before, since under a future scenario of climate change EW can potentially mitigate or alleviate drought effects in a certain extent within areas used for AR and BG plantation. Field and laboratory experiments are needed to quantify soil hydraulic changes under a natural and controlled environment. Besides that, investigation of potential changes of coupling EW with other terrestrial NETs such as Biochar is necessary, since Biochar and EW can increase the amount of soil organic matter, a variable also responsible for increasing water retention of soils.

We show that EW can be an important part of the solution to the problem of nutrient limitation AR and BG might suffer from. Specifically, the potential for hydrological management of soils was shown and it could be used in areas where seasonality and droughts might affect the biomass growth. The use of Enhanced Weathering for hydrological management coupled to land based NETs is worth to investigate. A global management of the carbon pools will need a full ecosystem understanding, addressing nutrient fluxes, and related soil mineralogy changes, soil hydrology, impacts on soil microorganisms, and responses of plants on the diverse array of soil types and climates. Applied ecosystem engineering is likely a future nexus discipline which needs to link local ecosystem processes with a global perspective on carbon pools within a universal effort to manage the carbon cycle.

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7. Author contribution

This article was conceived by the joint work of all authors, which participated in the discussions and writing, with the lead of WOG. The study was designed by W.O.G., J.H., and T.A.. W.O.G. compiled all the used data and conducted the calculations. K.K and A.P. supplied the MAgPIE model simulations and the stoichiometric ratios used for bioenergy grass. L.R.B. contributed to handling the JSBACH model outputs and D.G. contributed to the methodology to obtain the P-stock based demand for AR.

8. Competing interests

The authors declare that they have no conflict of interest.

9. References

Amann, T., and Hartmann, J.: Ideas and perspectives: Synergies from co-deployment of negative emission technologies, 2018.

Amiotte Suchet, P., Probst, J. L., and Ludwig, W.: Worldwide distribution of continental rock lithology: Implications for the atmospheric/soil CO2 uptake by continental weathering and alkalinity river transport to the oceans, Global Biogeochemical Cycles, 17, 2003.

Anda, M., Shamshuddin, J., Fauziah, C. I., and Omar, S. R. S.: Dissolution of Ground Basalt and Its Effect on Oxisol Chemical Properties and Cocoa Growth, Soil Science, 174, 264-271, 10.1097/SS.0b013e3181a56928, 2009.

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

Anda, M., Shamshuddin, J., and Fauziah, C. I.: Improving chemical properties of a highly weathered soil using finely ground basalt rocks, Catena, 124, 147-161, 10.1016/j.catena.2014.09.012, 2015.

https://doi.org/10.5194/bg-2019-386
Preprint. Discussion started: 9 October 2019
© Author(s) 2019. CC BY 4.0 License.

Appelo, C. A. J., and Postma, D.: Geochemistry, Groundwater and Pollution, Second Edition, 2005.

Aslyng, H.: Klima, jord og planter, Kulturteknik I, 5, 1976.

Augusto, L., Achat, D. L., Jonard, M., Vidal, D., and Ringeval, B.: Soil parent material-A major driver of plant nutrient limitations in terrestrial ecosystems, Glob Chang Biol, n/a-n/a, 10.1111/gcb.13691, 2017.

Bear, J.: Dynamics of fluids in porous media, American Elsevier., New York, 1972.

Beech, E., Rivers, M., Oldfield, S., and Smith, P.: GlobalTreeSearch: The first complete global database of tree species and country distributions, Journal of Sustainable Forestry, 36, 454-489, 2017.

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

Beringer, T., Lucht, W., and Schaphoff, S.: Bioenergy production potential of global biomass plantations under environmental and agricultural constraints, Gcb Bioenergy, 3, 299-312, 2011.

Berner, A. R. L., A. C., and Garrels, R. M.: The carbonate-silicate geochemical cycle and its effect on atmospheric carbon dioxide over the past 100 million years, Am J Sci, 283, 641-683, 1983.

Bissonnais, Y. L., and Singer, M. J.: Crusting, Runoff, and Erosion Response to Soil Water Content and Successive Rainfalls, Soil Science Society of America Journal, 56, 1898-1903, 10.2136/sssaj1992.03615995005600060042x, 1992.

Bodirsky, B. L., Popp, A., Weindl, I., Dietrich, J. P., Rolinski, S., Scheiffele, L., Schmitz, C., and Lotze-Campen, H.: N2O emissions from the global agricultural nitrogen cycle – current state and future scenarios, Biogeosciences, 9, 4169-4197, 10.5194/bg-9-4169-2012, 2012.

Bondeau, A., Smith, P. C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., LOTZE-CAMPEN, H., Müller, C., and Reichstein, M.: Modelling the role of agriculture for the 20th century global terrestrial carbon balance, Global Change Biology, 13, 679-706, 2007.

Bonsch, M., Humpenöder, F., Popp, A., Bodirsky, B., Dietrich, J. P., Rolinski, S., Biewald, A., Lotze-Campen, H., Weindl, I., Gerten, D., and Stevanovic, M.: Trade-offs between land and water requirements for large-scale bioenergy production, GCB Bioenergy, 8, 11-24, doi:10.1111/gcbb.12226, 2016.

Börker, J., Hartmann, J., Romero-Mujalli, G., and Li, G.: Aging of basalt volcanic systems and decreasing CO2 consumption by weathering, Earth Surface Dynamics, 1-9, 2018.

Bowen, M. E., McAlpine, C. A., House, A. P. N., and Smith, G. C.: Regrowth forests on abandoned agricultural land: A review of their habitat values for recovering forest fauna, Biological Conservation, 140, 273-296, https://doi.org/10.1016/j.biocon.2007.08.012, 2007.

Boysen, L. R., Lucht, W., and Gerten, D.: Trade-offs for food production, nature conservation and climate limit the terrestrial carbon dioxide removal potential, Global Change Biology, 23, 4303-4317, 10.1111/gcb.13745, 2017a.

https://doi.org/10.5194/bg-2019-386
Preprint. Discussion started: 9 October 2019
© Author(s) 2019. CC BY 4.0 License.

Boysen, L. R., Lucht, W., Gerten, D., Heck, V., Lenton, T. M., and Schellnhuber, H. J.: The limits to global-warming mitigation by terrestrial carbon removal, Earth's Future, 5, 463-474, 10.1002/2016EF000469, 2017b.

Cadoux, S., Riche, A. B., Yates, N. E., and Machet, J.-M.: Nutrient requirements of Miscanthus x giganteus: Conclusions from a review of published studies, Biomass and Bioenergy, 38, 14-22, https://doi.org/10.1016/j.biombioe.2011.01.015, 2012.

Calabrese, S., Porporato, A., and Parolari, A. J.: Hydrologic transport of dissolved inorganic carbon and its control on chemical weathering, Journal of Geophysical Research: Earth Surface, 122, 2016-2032, 2017.

Technical Bulletin: Fertilizer and Soil Acidity: https://www.adelaide.edu.au/fertiliser/publications/FactsheetAcid.pdf, access: 24 September.

Ciceri, D., de Oliveira, M., Stokes, R. M., Skorina, T., and Allanore, A.: Characterization of potassium agrominerals: Correlations between petrographic features, comminution and leaching of ultrapotassic syenites, Minerals Engineering, 102, 42-57, 10.1016/j.mineng.2016.11.016, 2017.

Clarkson, D. T., and Hanson, J. B.: The Mineral Nutrition of Higher Plants, Annual Review of Plant Physiology, 31, 239-298, 10.1146/annurev.pp.31.060180.001323, 1980.

Cornelissen, S., Koper, M., and Deng, Y. Y.: The role of bioenergy in a fully sustainable global energy system, Biomass and Bioenergy, 41, 21-33, https://doi.org/10.1016/j.biombioe.2011.12.049, 2012.

Council, N. R.: Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration, The National Academies Press, Washington, DC, 154 pp., 2015.

Creutzig, F.: Economic and ecological views on climate change mitigation with bioenergy and negative emissions, GCB Bioenergy, 8, 4-10, 10.1111/gcbb.12235, 2016.

Crowley, K. F., McNeil, B. E., Lovett, G. M., Canham, C. D., Driscoll, C. T., Rustad, L. E., Denny, E., Hallett, R. A., Arthur, M. A., Boggs, J. L., Goodale, C. L., Kahl, J. S., McNulty, S. G., Ollinger, S. V., Pardo, L. H., Schaberg, P. G., Stoddard, J. L., Weand, M. P., and Weathers, K. C.: Do Nutrient Limitation Patterns Shift from Nitrogen Toward Phosphorus with Increasing Nitrogen Deposition Across the Northeastern United States?, Ecosystems, 15, 940-957, 10.1007/s10021-012-9550-2, 2012.

Dietrich, J. P., Schmitz, C., Müller, C., Fader, M., Lotze-Campen, H., and Popp, A.: Measuring agricultural land-use intensity–A global analysis using a model-assisted approach, Ecological Modelling, 232, 109-118, 2012.

Dietrich, J. P., Schmitz, C., Lotze-Campen, H., Popp, A., and Müller, C.: Forecasting technological change in agriculture—an endogenous implementation in a global land use model, Technological Forecasting and Social Change, 81, 236-249, 2014.

Dietrich, J. P., Bodirsky, B. L., Weindl, I., Humpenöder, F., Stevanovic, M., Kreidenweis, U., Wang, X., Karstens, K., Mishra, A., Klein, D., Ambrósio, G., Araujo, E., Biewald, A., Lotze-Campen, H., and Popp, A.: MAgPIE – An Open Source land-use modeling framework – Version 4.0, doi:10.5281/zenodo.1418752, 2018.

Dietzen, C., Harrison, R., and Michelsen-Correa, S.: Effectiveness of enhanced mineral weathering as a carbon sequestration tool and alternative to agricultural lime: An incubation experiment, International Journal of Greenhouse Gas Control, 74, 251-258, https://doi.org/10.1016/j.ijggc.2018.05.007, 2018.

© Author(s) 2019. CC BY 4.0 License.

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

Elser, J. J., Bracken, M. E. S., Cleland, E. E., Gruner, D. S., Harpole, W. S., Hillebrand, H., Ngai, J. T., Seabloom, E. W., Shurin, J. B., and Smith, J. E.: Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems, Ecology Letters, 10, 1135-1142, doi:10.1111/j.1461-0248.2007.01113.x, 2007.

Fageria, N. K., and Baligar, V. C.: Chapter 7 Ameliorating Soil Acidity of Tropical Oxisols by Liming For Sustainable Crop Production, in: Advances in Agronomy, Academic Press, 345-399, 2008.

Fischer, G., Shah, M., van Velthuizen, H., and Nachtergaele, F. O.: Global agro-ecological assessment for agriculture in the 21st century, 2001.

Fishkis, O., Ingwersen, J., Lamers, M., Denysenko, D., and Streck, T.: Phytolith transport in soil: A field study using fluorescent labelling, Geoderma, 157, 27-36, https://doi.org/10.1016/j.geoderma.2010.03.012, 2010.

Gaillardet, J., Dupré, B., Louvat, P., and Allegre, C.: Global silicate weathering and CO2 consumption rates deduced from the chemistry of large rivers, Chemical geology, 159, 3-30, 1999.

Garcia, d. O. W., Amann, T., and Hartmann, J.: Increasing biomass demand enlarges negative forest nutrient budget areas in wood export regions, Scientific Reports, 8, 5280, 10.1038/s41598-018-22728-5, 2018.

Goll, D. S., Brovkin, V., Parida, B., Reick, C. H., Kattge, J., Reich, P. B., Van Bodegom, P., and Niinemets, Ü.: Nutrient limitation reduces land carbon uptake in simulations with a model of combined carbon, nitrogen and phosphorus cycling, Biogeosciences, 9, 3547-3569, 2012.

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

Goll, D. S., Winkler, A., Raddatz, T., Dong, N., Prentice, I. C., Ciais, P., and Brovkin, V.: Carbon-nitrogen interactions in idealized simulations with JSBACH (version 3.10), Geoscientific Model Development, 10, 2009-2030, 2017.

Goll, D. S., Joetzjer, E., Huang, M., and Ciais, P.: Low Phosphorus Availability Decreases Susceptibility of Tropical Primary Productivity to Droughts, Geophysical Research Letters, 45, 8231-8240, 10.1029/2018gl077736, 2018.

Grathwohl, P.: On equilibration of pore water in column leaching tests, Waste Management, 34, 908-918, https://doi.org/10.1016/j.wasman.2014.02.012, 2014.

Hartmann, J., and Kempe, S.: What is the maximum potential for CO2 sequestration by "stimulated" weathering on the global scale?, Naturwissenschaften, 95, 1159-1164, 10.1007/s00114-008-0434-4, 2008.

Hartmann, J., Jansen, N., Dürr, H. H., Kempe, S., and Köhler, P.: Global CO2-consumption by chemical weathering: What is the contribution of highly active weathering regions?, Global and Planetary Change, 69, 185-194, 2009.

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

Hartmann, J., Moosdorf, N., Lauerwald, R., Hinderer, M., and West, A. J.: Global chemical weathering and associated P-release - The role of lithology, temperature and soil properties, Chemical Geology, 363, 145-163, 10.1016/j.chemgeo.2013.10.025, 2014.

Haynes, R. J., and Swift, R. S.: Effects of soil acidification and subsequent leaching on levels of extractable nutrients in a soil, Plant and Soil, 95, 327-336, 10.1007/bf02374613, 1986.

He, Y., Zhu, Y., Smith, S., and Smith, F.: Interactions between soil moisture content and phosphorus supply in spring wheat plants grown in pot culture, 2002.

He, Y., Shen, Q., Kong, H., Xiong, Y., and Wang, X.: Effect of soil moisture content and phosphorus application on phosphorus nutrition of rice cultivated in different water regime systems, Journal of plant nutrition, 27, 2259-2272, 2005.

Herbert, D. A., and Fownes, J. H.: Phosphorus limitation of forest leaf area and net primary production on a highly weathered soil, Biogeochemistry, 29, 223-235, 10.1007/bf02186049, 1995.

Hesterberg, D.: Effects of stopping liming on abandoned agricultural land, Land Degradation & Development, 4, 257-267, 10.1002/ldr.3400040409, 1993.

Holtan, H., Kampnielsen, L., and Stuanes, A. O.: Phosphorus in Soil, Water and Sediment - an Overview, Hydrobiologia, 170, 19-34, Doi 10.1007/Bf00024896, 1988.

Hopkins, W. G., and Hüner, N. P. A.: Introduction to plant physiology, Ed. 4, John Wiley and Sons, 2008.

Humpenöder, F., Popp, A., Dietrich, J. P., Klein, D., Lotze-Campen, H., Bonsch, M., Bodirsky, B. L., Weindl, I., Stevanovic, M., and Müller, C.: Investigating afforestation and bioenergy CCS as climate change mitigation strategies, Environmental Research Letters, 9, 064029, 2014.

Hurtt, G. C., Chini, L. P., Frolking, S., Betts, R. A., Feddema, J., Fischer, G., Fisk, J. P., Hibbard, K., Houghton, R. A., Janetos, A., Jones, C. D., Kindermann, G., Kinoshita, T., Klein Goldewijk, K., Riahi, K., Shevliakova, E., Smith, S., Stehfest, E., Thomson, A., Thornton, P., van Vuuren, D. P., and Wang, Y. P.: Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands, Climatic Change, 109, 117, 10.1007/s10584-011-0153-2, 2011.

IGBP-DIS, S.: A program for creating global soil-property databases, IGBP Global Soils Data Task, France, 1998.

Johnson, A. H., Frizano, J., and Vann, D. R.: Biogeochemical implications of labile phosphorus in forest soils determined by the Hedley fractionation procedure, Oecologia, 135, 487-499, 10.1007/s00442-002-1164-5, 2003.

Jonard, M., Legout, A., Nicolas, M., Dambrine, E., Nys, C., Ulrich, E., Perre, R., and Ponette, Q.: Deterioration of Norway spruce vitality despite a sharp decline in acid deposition: a long-term integrated perspective, Global Change Biology, 18, 711-725, doi:10.1111/j.1365-2486.2011.02550.x, 2012.

https://doi.org/10.5194/bg-2019-386
Preprint. Discussion started: 9 October 2019
© Author(s) 2019. CC BY 4.0 License.

Kang, Y., Khan, S., and Ma, X.: Climate change impacts on crop yield, crop water productivity and food security – A review, Progress in Natural Science, 19, 1665-1674, https://doi.org/10.1016/j.pnsc.2009.08.001, 2009.

Kantola, I. B., Masters, M. D., Beerling, D. J., Long, S. P., and DeLucia, E. H.: Potential of global croplands and bioenergy crops for climate change mitigation through deployment for enhanced weathering, Biology Letters, 13, 10.1098/rsbl.2016.0714, 2017.

Kempe, S.: Carbon in the rock cycle, The global carbon cycle, 380, 343-375, 1979.

Knust, C., Schua, K., and Feger, K.-H.: Estimation of Nutrient Exports Resulting from Thinning and Intensive Biomass Extraction in Medium-Aged Spruce and Pine Stands in Saxony, Northeast Germany, Forests, 7, 302, 2016.

Kracher, D.: Nitrogen-Related Constraints of Carbon Uptake by Large-Scale Forest Expansion: Simulation Study for Climate Change and Management Scenarios, Earth's Future, 5, 1102-1118, 10.1002/2017EF000622, 2017.

La Scala, N., Bolonhezi, D., and Pereira, G. T.: Short-term soil CO2 emission after conventional and reduced tillage of a no-till sugar cane area in southern Brazil, Soil and Tillage Research, 91, 244-248, https://doi.org/10.1016/j.still.2005.11.012, 2006.

Landeweert, R., Hoffland, E., Finlay, R. D., Kuyper, T. W., and van Breemen, N.: Linking plants to rocks: ectomycorrhizal fungi mobilize nutrients from minerals, Trends in Ecology & Evolution, 16, 248-254, https://doi.org/10.1016/S0169-5347(01)02122-X, 2001.

Lenton, T. M., and Britton, C.: Enhanced carbonate and silicate weathering accelerates recovery from fossil fuel CO2 perturbations, Global Biogeochemical Cycles, 20, 2006.

Lenton, T. M.: The potential for land-based biological CO2 removal to lower future atmospheric CO2 concentration, Carbon Management, 1, 145-160, 2010.

Lenton, T. M.: The global potential for carbon dioxide removal, Geoengineering of the Climate System, 52-79, 2014.

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

Liu, S., Han, C., Liu, J., and Li, H.: Hydrothermal decomposition of potassium feldspar under alkaline conditions, Rsc Advances, 5, 93301-93309, 2015.

Lotze-Campen, H., Müller, C., Bondeau, A., Rost, S., Popp, A., and Lucht, W.: Global food demand, productivity growth, and the scarcity of land and water resources: a spatially explicit mathematical programming approach, Agricultural Economics, 39, 325-338, 2008.

Ma, X., Ma, H., and Yang, J.: Sintering Preparation and Release Properties of K2MgSi3O8 Slow-Release Fertilizer Using Biotite Acid-Leaching Residues as Silicon Source, Industrial & Engineering Chemistry Research, 55, 10926-10931, 2016a.

Ma, X., Yang, J., Ma, H., and Liu, C.: Hydrothermal extraction of potassium from potassic quartz syenite and preparation of aluminum hydroxide, International Journal of Mineral Processing, 147, 10-17, 2016b.

Madsen, H. B.: Distribution of spring barley roots in Danish soils, of different texture and under different climatic conditions, Plant and Soil, 88, 31-43, 10.1007/bf02140664, 1985.

Menge, D. N. L., Hedin, L. O., and Pacala, S. W.: Nitrogen and Phosphorus Limitation over Long-Term Ecosystem Development in Terrestrial Ecosystems, PLoS ONE, 7, e42045, 10.1371/journal.pone.0042045, 2012.

Mersi, W. V., Kuhnert-Finkernagel, R., and Schinner, F.: The influence of rock powders on microbial activity of three forest soils, Z Pflanz Bodenkunde, 155, 29-33, doi:10.1002/jpln.19921550107, 1992.

Müller, C., and Robertson, R. D.: Projecting future crop productivity for global economic modeling, Agricultural Economics, 45, 37-50, 10.1111/agec.12088, 2013.

Munkholm, L. J., Schjønning, P., and Sørensen, H.: Jordpakning og mekanisk løsning på grovsandet jord, Ministeriet for Fødevarer, Landbrug og Fiskeri,, Viborg, 6, 2003.

Nkouathio, D. G., Wandji, P., Bardintzeff, J. M., Tematio, P., Kagou Dongmo, A., and Tchoua, F.: Utilisation des roches volcaniques pour la remineralisation des sols ferrallitiques des regions tropicales. Cas des pyroclastites basaltiques du graben de Tombel (Ligne volcanique du Cameroun), Bull. Soc. Vaudoise Sci. Nat., 14, 2008.

Nunes, J. M. G., Kautzmann, R. M., and Oliveira, C.: Evaluation of the natural fertilizing potential of basalt dust wastes from the mining district of Nova Prata (Brazil), Journal of Cleaner Production, 84, 649-656, 10.1016/j.jclepro.2014.04.032, 2014.

Olsen, M.: Orienterende forsøg vedrørende jordes dybdebehandling, Hedeselskabets Forskningsvirksomhed, Viborg, 41, 1958.

Oren, R., Ellsworth, D. S., Johnsen, K. H., Phillips, N., Ewers, B. E., Maier, C., Schafer, K. V., McCarthy, H., Hendrey, G., McNulty, S. G., and Katul, G. G.: Soil fertility limits carbon sequestration by forest ecosystems in a CO2-enriched atmosphere, Nature, 411, 469-472, 10.1038/35078064, 2001.

Pardo, L. H., Robin-Abbott, M., Duarte, N., and Miller, E., K.: Tree Chemistry Database (Version 1.0), United States Department of Agriculture, NE-324. Newtown Square PA, Gen. Tech. Rep., 45, 2005.

Popp, A., Lotze-Campen, H., and Bodirsky, B.: Food consumption, diet shifts and associated non-CO2 greenhouse gases from agricultural production, Global Environmental Change, 20, 451-462, 2010.

Popp, A., Lotze-Campen, H., Leimbach, M., Knopf, B., Beringer, T., Bauer, N., and Bodirsky, B.: On sustainability of bioenergy production: Integrating co-emissions from agricultural intensification, Biomass and Bioenergy, 35, 4770-4780, https://doi.org/10.1016/j.biombioe.2010.06.014, 2011.

Popp, A., Calvin, K., Fujimori, S., Havlik, P., Humpenöder, F., Stehfest, E., Bodirsky, B. L., Dietrich, J. P., Doelmann, J. C., Gusti, M., Hasegawa, T., Kyle, P., Obersteiner, M., Tabeau, A., Takahashi, K., Valin, H., Waldhoff, S., Weindl, I., Wise, M., Kriegler, E., Lotze-Campen, H., Fricko, O., Riahi, K., and Vuuren, D. P. v.: Land-use futures in the shared socio-economic pathways, Global Environmental Change, 42, 331-345, https://doi.org/10.1016/j.gloenvcha.2016.10.002, 2017.

Reick, C. H., Raddatz, T., Brovkin, V., and Gayler, V.: Representation of natural and anthropogenic land cover change in MPI-ESM, Journal of Advances in Modeling Earth Systems, 5, 459-482, 10.1002/jame.20022, 2013.

Reicosky, D. C.: Tillage-induced CO2 emission from soil, Nutrient Cycling in Agroecosystems, 49, 273-285, 10.1023/A:1009766510274, 1997.

https://doi.org/10.5194/bg-2019-386
Preprint. Discussion started: 9 October 2019
© Author(s) 2019. CC BY 4.0 License.

Renforth, P.: The potential of enhanced weathering in the UK, International Journal of Greenhouse Gas Control, 10, 229-243, 10.1016/j.ijggc.2012.06.011, 2012.

Renforth, P., von Strandmann, P. A. E. P., and Henderson, G. M.: The dissolution of olivine added to soil: Implications for enhanced weathering, Applied Geochemistry, 61, 109-118, 10.1016/j.apgeochem.2015.05.016, 2015.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin Iii, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R. W., Fabry, V. J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., and Foley, J. A.: A safe operating space for humanity, Nature, 461, 472, 10.1038/461472a, 2009.

Romero-Mujalli, G., Hartmann, J., Börker, J., Gaillardet, J., and Calmels, D.: Ecosystem controlled soil-rock pCO2 and carbonate weathering – Constraints by temperature and soil water content, Chemical Geology, https://doi.org/10.1016/j.chemgeo.2018.01.030, 2018.

Rossato, L., Alvalá, R. C. d. S., Marengo, J. A., Zeri, M., Cunha, A. P. M. d. A., Pires, L. B. M., and Barbosa, H. A.: Impact of Soil Moisture on Crop Yields over Brazilian Semiarid, Frontiers in Environmental Science, 5, 10.3389/fenvs.2017.00073, 2017.

Sadras, V. O., and Milroy, S. P.: Soil-water thresholds for the responses of leaf expansion and gas exchange: A review, Field Crop Res, 47, 253-266, https://doi.org/10.1016/0378-4290(96)00014-7, 1996.

Sairam, R.: PHYSIOLOGY OF WATERLOGGING TOLERANCE IN PLANTS, National Seminar on Sustainable Crop Productivity through Physiological Interventions, 2011, 9,

Saxton, K. E., and Rawls, W. J.: Soil water characteristic estimates by texture and organic matter for hydrologic solutions, Soil science society of America Journal, 70, 1569-1578, 2006.

Schaap, M. G., Leij, F. J., and van Genuchten, M. T.: rosetta: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions, Journal of Hydrology, 251, 163-176, https://doi.org/10.1016/S0022-1694(01)00466-8, 2001.

Schuiling, R. D., and Krijgsman, P.: Enhanced Weathering: An Effective and Cheap Tool to Sequester Co2, Climatic Change, 74, 349-354, 10.1007/s10584-005-3485-y, 2006.

Sharpley, A.: Phosphorus availability. CRC Press. Boca Raton Florida. pp. D18-D37, 2000.

Shen, J., Yuan, L., Zhang, J., Li, H., Bai, Z., Chen, X., Zhang, W., and Zhang, F.: Phosphorus Dynamics: From Soil to Plant, Plant Physiology, 156, 997-1005, 10.1104/pp.111.175232, 2011.

Shinjini, G., C., F. M., A., V. M., Mariann, G. J., D., Y. R., and J., F. T.: Phosphorus limitation of aboveground production in northern hardwood forests, Ecology, 99, 438-449, doi:10.1002/ecy.2100, 2018.

Smeets, E. M. W., and Faaij, A. P. C.: Bioenergy potentials from forestry in 2050, Climatic Change, 81, 353-390, 10.1007/s10584-006-9163-x, 2007.

Smith, P.: Agricultural greenhouse gas mitigation potential globally, in Europe and in the UK: what have we learnt in the last 20 years?, Global Change Biology, 18, 35-43, 10.1111/j.1365-2486.2011.02517.x, 2012.

Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R. B., Cowie, A., Kriegler, E., van Vuuren, D. P., Rogelj, J., Ciais, P., Milne, J., Canadell, J. G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grübler, A., Heidug, W. K., Jonas, M., Jones, C. D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J. R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., and Yongsung, C.: Biophysical and economic limits to negative CO2 emissions, Nature Climate Change, 6, 42, 10.1038/nclimate2870 https://www.nature.com/articles/nclimate2870#supplementary-information, 2015.

Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R. B., Cowie, A., Kriegler, E., van Vuuren, D. P., Rogelj, J., Ciais, P., Milne, J., Canadell, J. G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grubler, A., Heidug, W. K., Jonas, M., Jones, C. D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J. R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., and Yongsung, C.: Biophysical and economic limits to negative CO2 emissions, Nature Clim. Change, 6, 42-50, 10.1038/nclimate2870 http://www.nature.com/nclimate/journal/v6/n1/abs/nclimate2870.html#supplementary-information, 2016.

Smith, W. K., Zhao, M., and Running, S. W.: Global Bioenergy Capacity as Constrained by Observed Biospheric Productivity Rates, BioScience, 62, 911-922, 10.1525/bio.2012.62.10.11, 2012.

Stefánsson, A., Gíslason, S. R., and Arnórsson, S.: Dissolution of primary minerals in natural waters: II. Mineral saturation state, Chemical Geology, 172, 251-276, 2001.

Straaten, P. v.: Agrogeology: the use of rocks for crops, 631.4 S894, Enviroquest, 2007.

Strefler, J., Amann, T., Bauer, N., Kriegler, E., and Hartmann, J.: Potential and costs of Carbon Dioxide Removal by Enhanced Weathering of rocks, Environmental Research Letters, 2018.

Sun, Y., Peng, S., Goll, D. S., Ciais, P., Guenet, B., Guimberteau, M., Hinsinger, P., Janssens, I. A., Peñuelas, J., Piao, S., Poulter, B., Violette, A., Yang, X., Yin, Y., and Zeng, H.: Diagnosing phosphorus limitations in natural terrestrial ecosystems in carbon cycle models, Earth's Future, 10.1002/2016ef000472, 2017.

Tanner, E. V. J., Vitousek, P. M., and Cuevas, E.: Experimental investigation of nutrient limitation of forest growth on wet tropical mountains, Ecology, 79, 10-22, 1998.

Taylor, L. L., Leake, J. R., Quirk, J., Hardy, K., Banwart, S. A., and Beerling, D. J.: Biological weathering and the long-term carbon cycle: integrating mycorrhizal evolution and function into the current paradigm, Geobiology, 7, 171-191, 10.1111/j.1472-4669.2009.00194.x, 2009.

Taylor, L. L., Quirk, J., Thorley, R. M. S., Kharecha, P. A., Hansen, J., Ridgwell, A., Lomas, M. R., Banwart, S. A., and Beerling, D. J.: Enhanced weathering strategies for stabilizing climate and averting ocean acidification, Nature Climate Change, 6, 402-406, 10.1038/nclimate2882, 2015.

Theodoro, S. H., de Souza Martins, E., Fernandes, M. M., and de Carvalho, A. M. X.: II Congresso Brasileiro de Rochagem, 2013.

Thomson, A. M., Calvin, K. V., Smith, S. J., Kyle, G. P., Volke, A., Patel, P., Delgado-Arias, S., Bond-Lamberty, B., Wise, M. A., Clarke, L. E., and Edmonds, J. A.: RCP4.5: a pathway for stabilization of radiative forcing by 2100, Climatic Change, 109, 77, 10.1007/s10584-011-0151-4, 2011.

Tokimatsu, K., Yasuoka, R., and Nishio, M.: Global zero emissions scenarios: The role of biomass energy with carbon capture and storage by forested land use, Applied Energy, 185, 1899-1906, https://doi.org/10.1016/j.apenergy.2015.11.077, 2017.

Uhlig, D.: The deep Critical Zone as a source of mineral nutrients to montane, temperate forest ecosystems, 2019.

Vergutz, L., Manzoni, S., Porporato, A., Novais, R. F., and Jackson, R. B.: A Global Database of Carbon and Nutrient Concentrations of Green and Senesced Leaves. ORNL Distributed Active Archive Center, 2012.

Vienken, T., and Dietrich, P.: Field evaluation of methods for determining hydraulic conductivity from grain size data, Journal of Hydrology, 400, 58-71, 2011.

Vitousek, P. M., Aber, J. D., Howarth, R. W., Likens, G. E., Matson, P. A., Schindler, D. W., Schlesinger, W. H., and Tilman, D. G.: Human alteration of the global nitrogen cycle: sources and consequences, Ecological applications, 7, 737-750, 1997.

Vitousek, P. M., Porder, S., Houlton, B. Z., and Chadwick, O. A.: Terrestrial phosphorus limitation: mechanisms, implications, and nitrogen–phosphorus interactions, Ecological Applications, 20, 5-15, 10.1890/08-0127.1, 2010.

von Liebig, J. F., and Playfair, L. P. B.: Chemistry in its application to agriculture and physiology, JM Campbell, 1843.

Von Wilpert, K., and Lukes, M.: Ecochemical effects of phonolite rock powder, dolomite and potassium sulfate in a spruce stand on an acidified glacial loam, Nutrient Cycling in Agroecosystems, 65, 115-127, 2003.

Walker, J. C., Hays, P., and Kasting, J. F.: A negative feedback mechanism for the long-term stabilization of Earth's surface temperature, Journal of Geophysical Research: Oceans, 86, 9776-9782, 1981.

Wang, R., Goll, D., Balkanski, Y., Hauglustaine, D., Boucher, O., Ciais, P., Janssens, I., Penuelas, J., Guenet, B., Sardans, J., Bopp, L., Vuichard, N., Zhou, F., Li, B., Piao, S., Peng, S., Huang, Y., and Tao, S.: Global forest carbon uptake due to nitrogen and phosphorus deposition from 1850 to 2100, Global Change Biology, 23, 4854-4872, doi:10.1111/gcb.13766, 2017.

Wang, Y. P., Law, R. M., and Pak, B.: A global model of carbon, nitrogen and phosphorus cycles for the terrestrial biosphere, Biogeosciences, 7, 2261-2282, 10.5194/bg-7-2261-2010, 2010.

Whitfield, C. J., and Reid, C.: Predicting surface area of coarse-textured soils: Implications for weathering rates, Canadian Journal of Soil Science, 93, 621-630, 2013.

https://doi.org/10.5194/bg-2019-386
Preprint. Discussion started: 9 October 2019
© Author(s) 2019. CC BY 4.0 License.

Wösten, J. H. M., Pachepsky, Y. A., and Rawls, W. J.: Pedotransfer functions: bridging the gap between available basic soil data and missing soil hydraulic characteristics, Journal of Hydrology, 251, 123-150, https://doi.org/10.1016/S0022-1694(01)00464-4, 2001.

Wright, S. J., Yavitt, J. B., Wurzburger, N., Turner, B. L., Tanner, E. V., Sayer, E. J., Santiago, L. S., Kaspari, M., Hedin, L. O., and Harms, K. E.: Potassium, phosphorus, or nitrogen limit root allocation, tree growth, or litter production in a lowland tropical forest, Ecology, 92, 1616-1625, 2011.

Yang, X., Post, W. M., Thornton, P. E., and Jain, A. K.: Global Gridded Soil Phosphorus Distribution Maps at 0.5-degree Resolution. ORNL Distributed Active Archive Center, 2014a.

Yang, X., Thornton, P. E., Ricciuto, D. M., and Post, W. M.: The role of phosphorus dynamics in tropical forests – a modeling study using CLM-CNP, Biogeosciences, 11, 1667-1681, 10.5194/bg-11-1667-2014, 2014b.

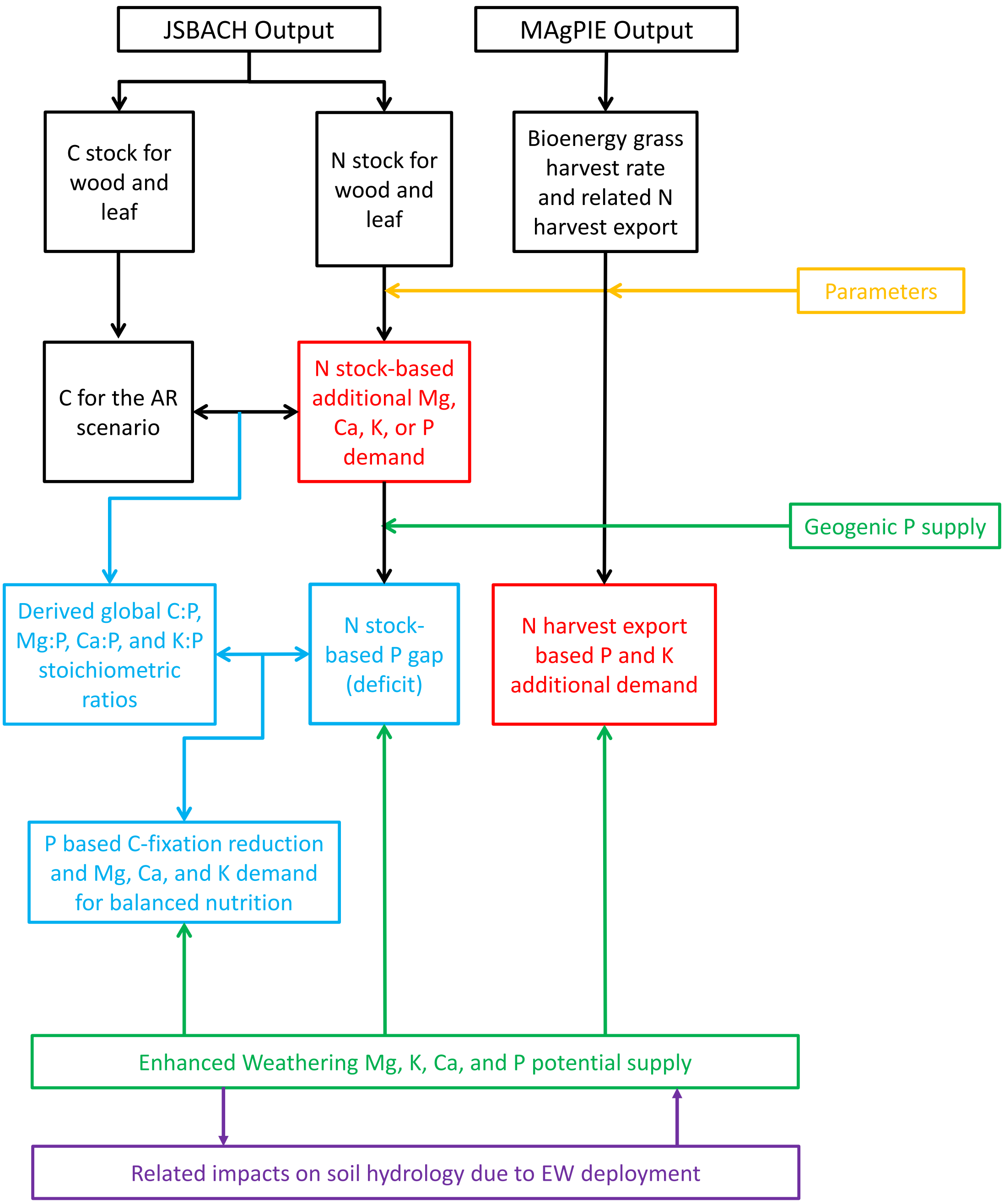

Fig. 1: Schematic steps and datasets used to derive geogenic nutrient demand from simulated biomass changes, P gaps, reduced C sequestration, and Ca, K, and Mg supply for balanced tree nutrition. Black colors: Outputs from land surface model JSBACH and agricultural production model MAgPIE. Yellow colors: stoichiometric Mg:N, Ca:N, K:N, and P:N ratios used to obtain the N stock-based nutrient demand. Red colors: N stock-based P, Mg, Ca, and K demand for wood and leaf (AR) or N harvest export based P and K demand (BG). Green colors: nutrient supply from geogenic sources (atmospheric P deposition and different soil P pools) or from Enhanced Weathering. Blue colors: derived P gap for AR, derived stoichiometric C:P, Mg:P, Ca:P, and K:P ratios, P based

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C-fixation reduction, and P based Mg, Ca, and K supply for balanced tree nutrition. Purple colors: Related EW deployment impacts on soil hydrology estimated by pedotransfer functions. AR: Afforestation/reforestation, BG: Bio-energy grass.

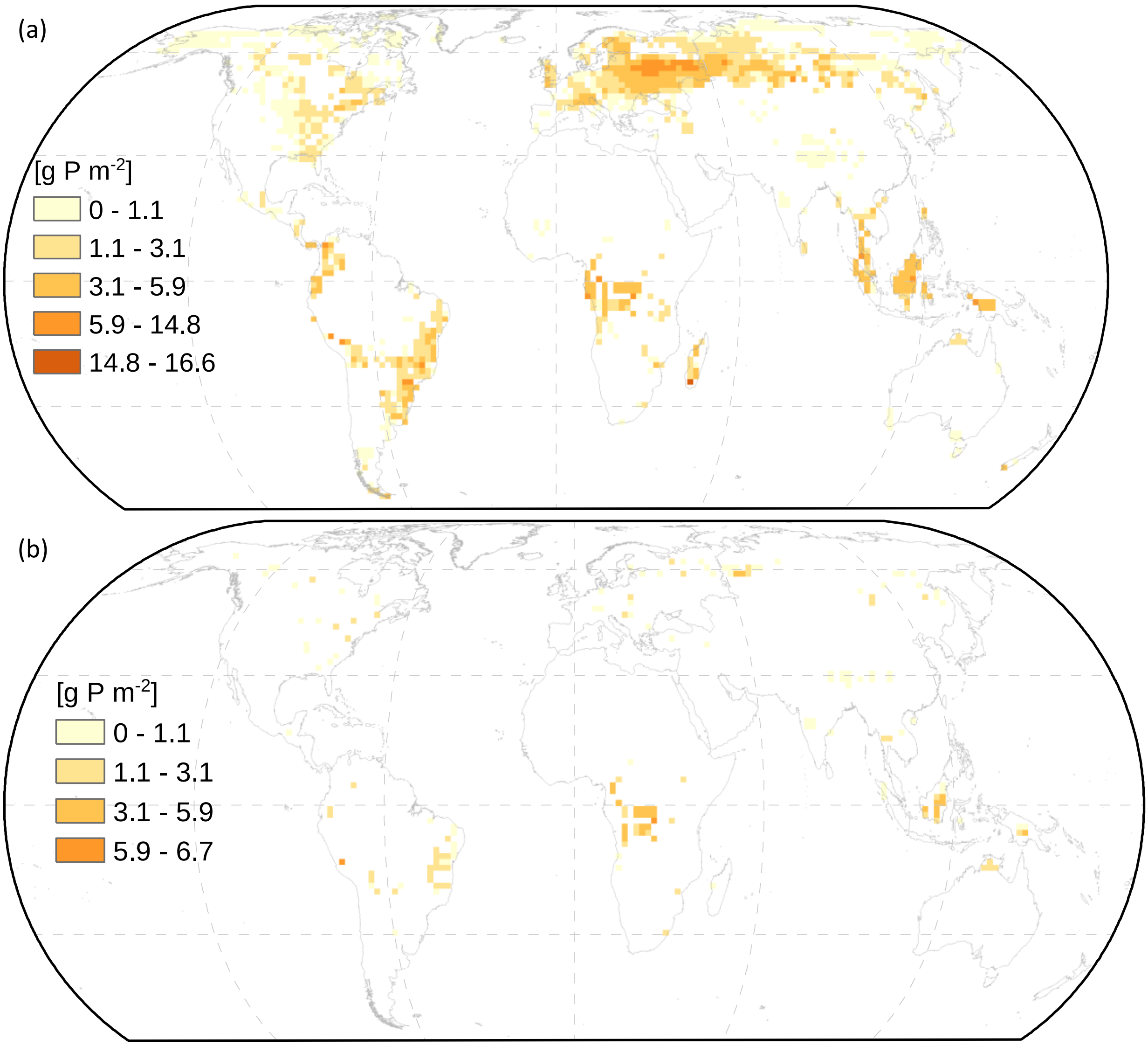

Fig. 2: Areas with potential P gap for the nutrient budget of the N-limited AR scenario (after 94 years of simulation) assuming P concentrations within foliar and wood material corresponding to mean values (Table 1). a) Geogenic P supply scenario one (geogenic P from weathering plus atmospheric P deposition as source of P). b) Geogenic P supply scenario two (geogenic P from soil inorganic labile P and organic P pools plus atmospheric P deposition and P from weathering as source of P). Map generated with ESRI ArcGIS 10.6 (http://www.esri.com).

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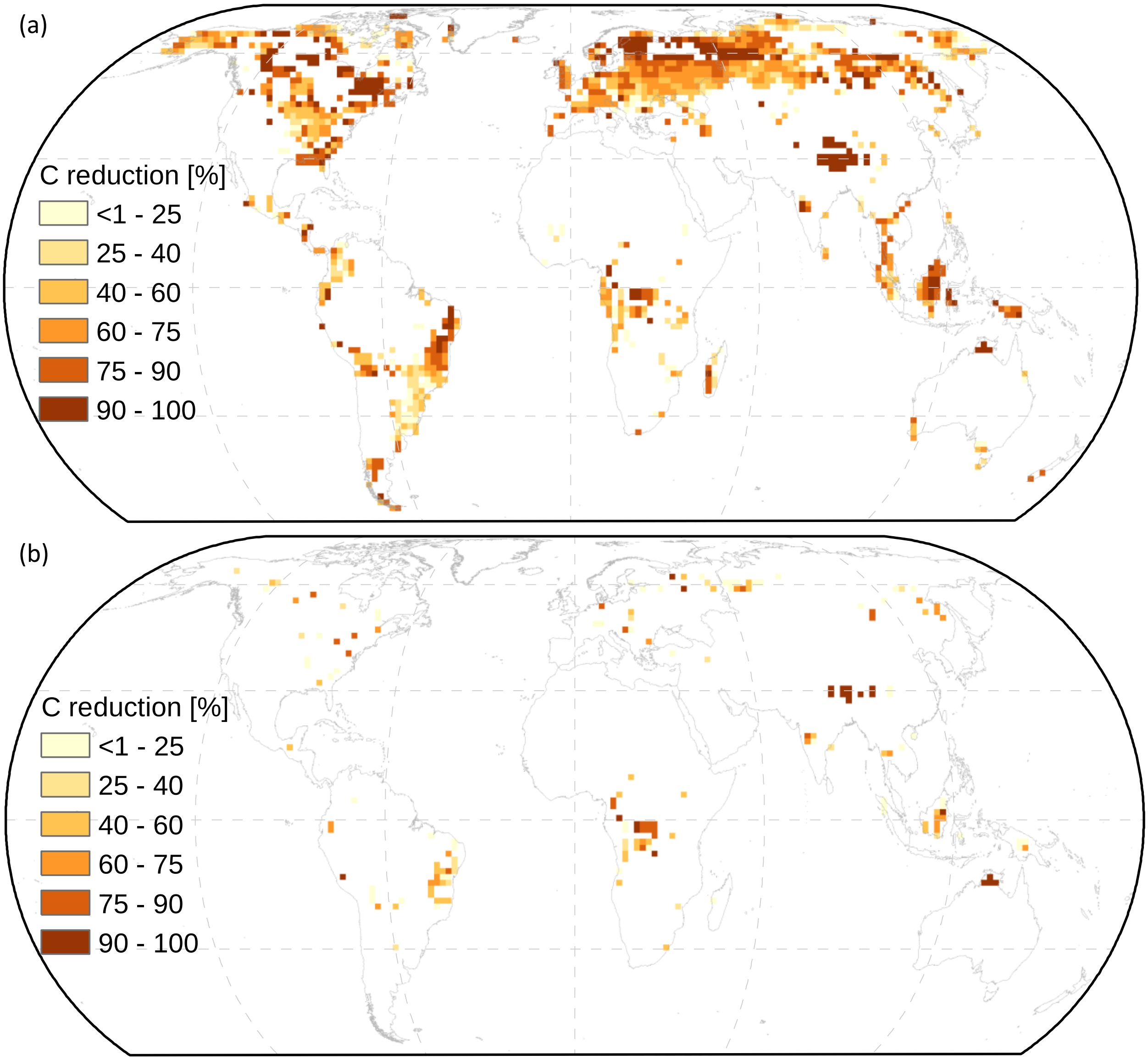

815 **Fig. 3: Reduction on forest C sequestration due to geogenic P limitation. C-reduction estimated from stoichiometric C:P ratios for the N-limited AR scenario assuming P concentrations within foliar and wood material corresponding to mean values (Table 1). a) C-reduction based on P gaps of Fig. 2a, obtained for geogenic P supply scenario one (geogenic P from weathering plus atmospheric P deposition as source of P). b) C-reduction based on P gaps of Fig. 2b, obtained for geogenic P supply scenario two (geogenic P from soil inorganic labile P and organic P pools plus atmospheric P deposition and P from weathering as source of P). For resulting global**
820 **C reduction check Table 3. Map generated with ESRI ArcGIS 10.6 (http://www.esri.com).**

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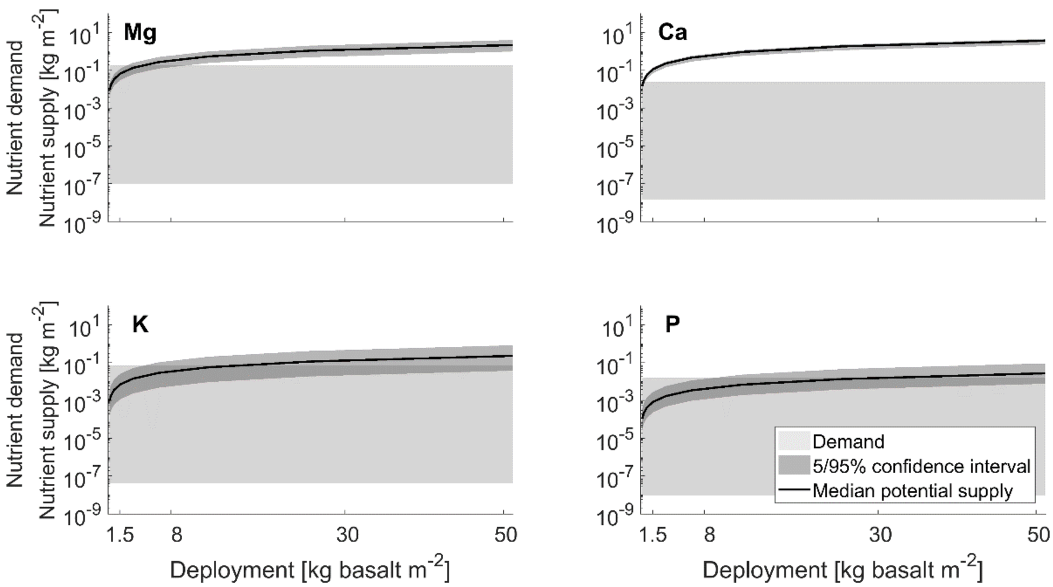
(a)



(b)

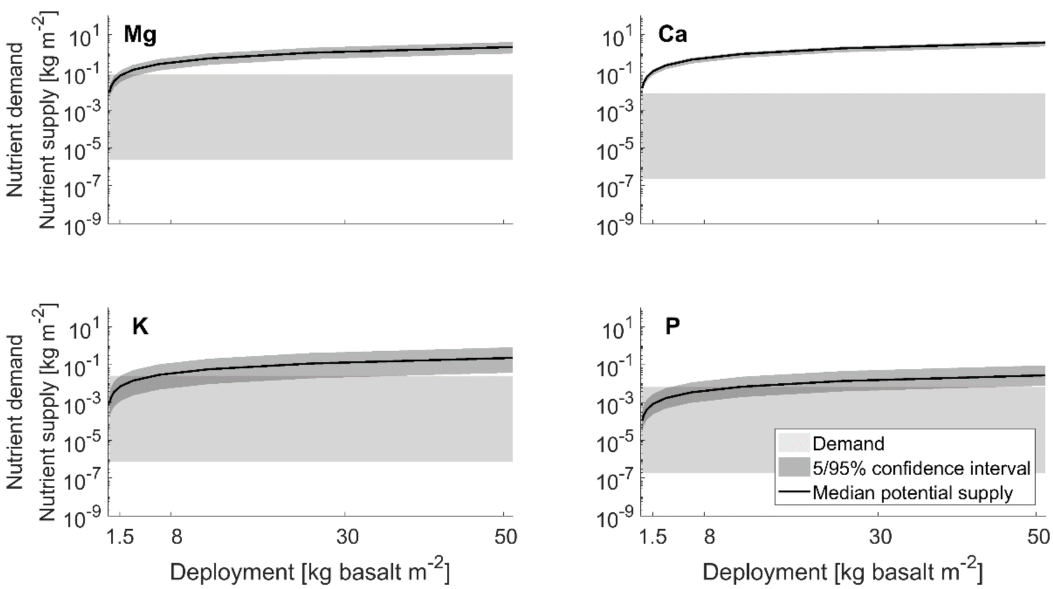


Fig. 4: Mg, Ca, K, and P supply by basalt dissolution (logarithmic curve) given as median and 5/95% confidence intervals (dark grey areas). Horizontal filled boxes indicate the nutrient demand for maximum (17.1 g P m^{-2}) and minimum (<<1 g P m^{-2}) gap of each geogenic P supply scenario for P and derived Mg, Ca, and K demand for balanced tree nutrition assuming mean foliar and wood material chemistry (Table 1). a) Based on minimum and maximum P gap values of <1 g P m^{-2} and 17.1 g P m^{-2}, which were obtained for a geogenic P supply scenario one (geogenic P from weathering plus atmospheric P deposition as source of P). b) Based on minimum and maximum P gap values of <1 g P m^{-2} and 6.6 g P m^{-2}, which were obtained for a geogenic P supply scenario two (geogenic P from soil inorganic labile P and organic P pools plus atmospheric P deposition and P from weathering as source of P).

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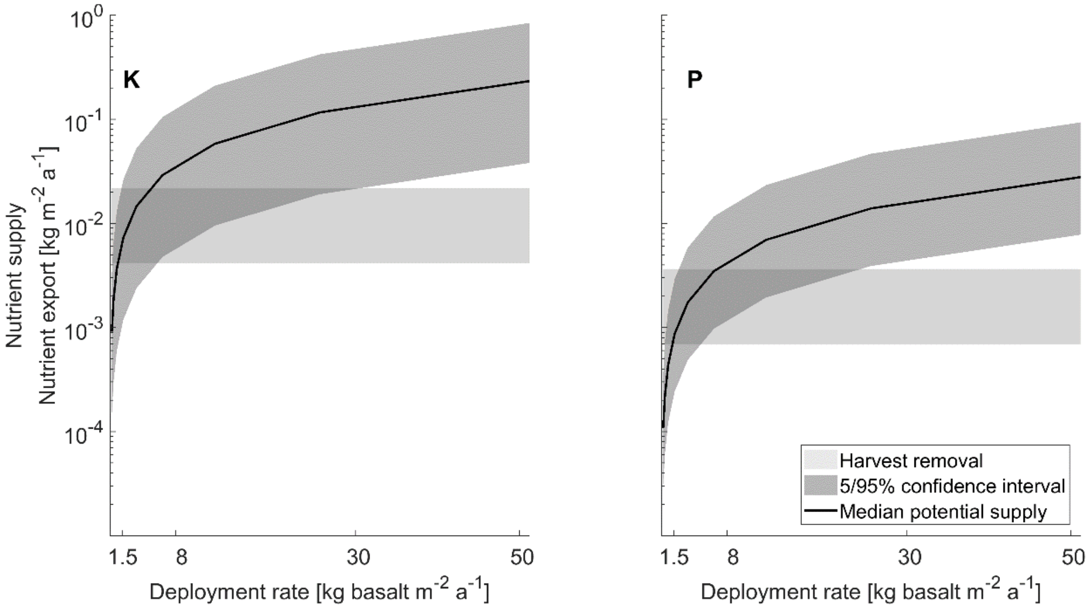

Fig. 5: Projected K and P supply (logarithmic curve) by basalt dissolution given as median and 5/95% confidence interval for bio-energy grasses K and P demand (horizontal filled boxes) based on global minimum 0.7 kg m-2 a-1 and maximum 3.6 kg m-2 a-1 harvest rates for simulation years of 1995 – 2090.

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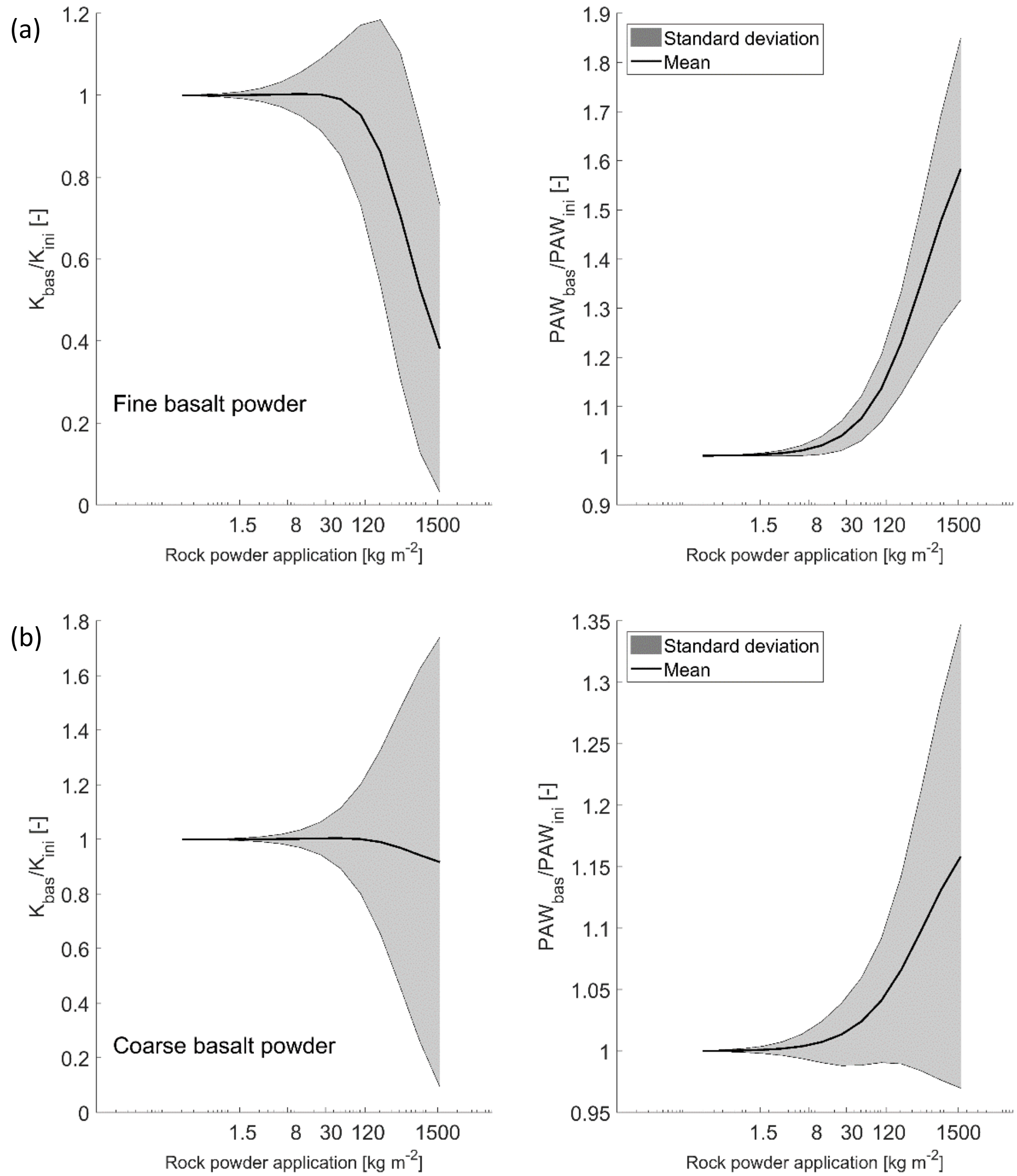

Fig. 6: Relative impacts on soil saturated hydraulic conductivity (K_S) and Plant Available Water (PAW). K_{bas} and PAW_{bas} respectively represent the estimated soil K_S and PAW after basalt application. K_{ini} is the estimated initial soil K_S and PAW_{ini} is the estimated initial PAW of different soils. a) Application of a fine basalt texture (15.6% clay, 83.8% silt, and 0.6% fine sand). b) Application of a coarse basalt texture (15.6% clay, 53.8% silt, and 30.6% fine sand) for areas corresponding to P gaps of geogenic P supply scenario one, for the N-unlimited AR scenario (Supplement S1 Fig. S21a). Mean and standard deviations for n=1525 grid cells. *cf.*, Supplement S1 section S5 for impacts on initial K_S and PAW of fine or coarse basalt powder texture on soils of P gap areas from b.

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Table 1: Stoichiometric parameters for different pools and biomes used in this study.

Biome		Tropical evergreen					Tropical deciduous					Temperate evergreen				
Leaf[a]		mean	Std	n	5th percentile	95th percentile	mean	Std	n	5th percentile	95th percentile	mean	Std	n	5th percentile	95th percentile
C:N	[-]	29.72	15.01	4	16.33	46.49	26.96*	10.53*	171*	14.50*	46.7*	49.11	12.15	8	33.54	65.69
P:N		0.06	0.02	59	0.04	0.10	0.07	0.03	43	0.04	0.13	0.09	0.03	23	0.05	0.13
K:N		0.97	0.80	2	0.46	1.48	1.26	0.93	22	0.23	2.45	0.47	0.09	12	0.33	0.58
Ca:N		2.73	3.44	2	0.54	4.91	1.55	0.78	22	0.52	2.90	0.73*	0.67*	150*	0.16*	1.94*
Mg:N		0.40	0.52	2	0.07	0.73	0.37	0.29	22	0.10	0.83	0.21*	0.21*	115*	0.05*	0.66*
Wood[b]		mean	Std	n	5th percentile	95th percentile	mean	Std	n	5th percentile	95th percentile	mean	Std	n	5th percentile	95th percentile
C:N	[-]	235	244	9	56	610	235	244	9	56	610	235	244	9	56	610
P:N		0.15	0.20	684	0.04	0.30	0.15	0.20	684	0.04	0.30	0.15	0.20	684	0.04	0.30
K:N		0.60	0.40	700	0.20	1.20	0.60	0.40	700	0.20	1.20	0.60	0.40	700	0.20	1.20
Ca:N		1.80	1.30	705	0.40	4.30	1.80	1.30	705	0.40	4.30	1.80	1.30	705	0.40	4.30
Mg:N		0.20	0.10	681	0.10	0.40	0.20	0.10	681	0.10	0.40	0.20	0.10	681	0.10	0.40

Biome		Temperate deciduous					Shrubs raingreen					Shrubs deciduous				
Leaf[a]		mean	Std	n	5th percentile	95th percentile	mean	Std	n	5th percentile	95th percentile	mean	Std	n	5th percentile	95th percentile
C:N	[-]	55.30	12.02	2	47.65	62.95	26.31	6.83	2	21.97	30.65	26.96*	10.53*	171*	14.5*	46.70*
P:N		0.08	0.03	32	0.04	0.13	0.07	0.01	2	0.06	0.08	0.08*	0.05*	662*	0.04*	0.16*
K:N		0.43	0.13	23	0.24	0.61	0.38	0.02	2	0.37	0.39	0.59*	0.45*	207*	0.24*	1.50*
Ca:N		0.73*	0.67*	150*	0.16*	1.94*	0.44	0.08	2	0.39	0.50	0.73*	0.67*	150*	0.16*	1.94*
Mg:N		0.21*	0.21*	115*	0.05*	0.66*	0.09	0.04	2	0.06	0.12	0.21*	0.21*	115*	0.05*	0.66*
Wood[b]		mean	Std	n	5th percentile	95th percentile	mean	Std	n	5th percentile	95th percentile	mean	Std	n	5th percentile	95th percentile
C:N	[-]	235	244	9	56	610	235	244	9	56	610	235	244	9	56	610
P:N		0.15	0.20	684	0.04	0.30	0.15	0.20	684	0.04	0.30	0.15	0.20	684	0.04	0.30
K:N		0.60	0.40	700	0.20	1.20	0.60	0.40	700	0.20	1.20	0.60	0.40	700	0.20	1.20
Ca:N		1.80	1.30	705	0.40	4.30	1.80	1.30	705	0.40	4.30	1.80	1.30	705	0.40	4.30
Mg:N		0.20	0.10	681	0.10	0.40	0.20	0.10	681	0.10	0.40	0.20	0.10	681	0.10	0.40

*Values obtained from all biomes. [a] Stoichiometric ratios derived from a global leaf chemistry database (Vergutz et al., 2012). [b] Stoichiometric ratios derived from a US soft- and hardwood database (Pardo et al., 2005). *cf.*, SI-table.xlsx file for used database.

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Table 2: Geogenic P sources used for each geogenic P supply scenario.

P source	Resolution	Geogenic P supply scenario one	Geogenic P supply scenario two	Reference
Soil organic P and inorganic labile P	0.5°		X	(Yang et al., 2014a)
Atmospheric P deposition	1°	X	X	(Wang et al., 2017)
Geogenic P release rates	1 km^2	X	X	(Hartmann et al., 2014)

Table 3: Global P gap, maximum estimated P gap, maximum C sequestration reduction, and global C reduction for the natural N supply (N-limited) AR scenario (projected C sequestration of 190 Gt C).

N supply	Geogenic P supply	Maximum estimated P gap [g P m^{-2}]			Global P gap [Mt P]			Maximum C sequestration reduction [kg C m^{-2}]			Global C reduction [Gt C]		
		Wood and leaves P content											
		5^{th} percentile	Mean	95^{th} percentile	5^{th} percentile	Mean	95^{th} percentile	5^{th} percentile	mean	95^{th} percentile	5^{th} percentile	mean	95^{th} percentile
Limited	Scenario one	4.1	16.6	30.2	9.2	76.6	181.0	9.7	14.5	15.6	23.0	71.0	98.0
	Scenario two	1.6	6.7	12.2	1.0	9.9	34.7	4.7	6.2	6.5	3.0	9.5	19.0

Table 4: Minimum and maximum soil hydraulic conductivity for areas coincident to the P gap areas of each geogenic P supply scenario one, for the N-unlimited AR scenario (Supplement S1 Fig. S21a).

	Geogenic P supply scenario one	Geogenic P supply scenario two
	Hydraulic conductivity (K) [m s^{-1}]	
Min	1.5×10^{-7}	2.7×10^{-7}
Max	1.7×10^{-4}	7.8×10^{-5}
	Plant available water (PAW) [%]	
Min	4	6
Max	32	28