Supplement of Biogeosciences, 16, 2949–2960, 2019
https://doi.org/10.5194/bg-16-2949-2019-supplement

Biogeosciences
Open Access

Supplement of

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

Thorben Amann and Jens Hartmann

Correspondence to: Thorben Amann (science@thorbenamann.de)

S1. Development of global potassium/potash resources

Manning (2015) described the development of global potassium resources. Here we took the underlying data to recreate the figure, extended by the two most recent years as available (Fig. S1-1).

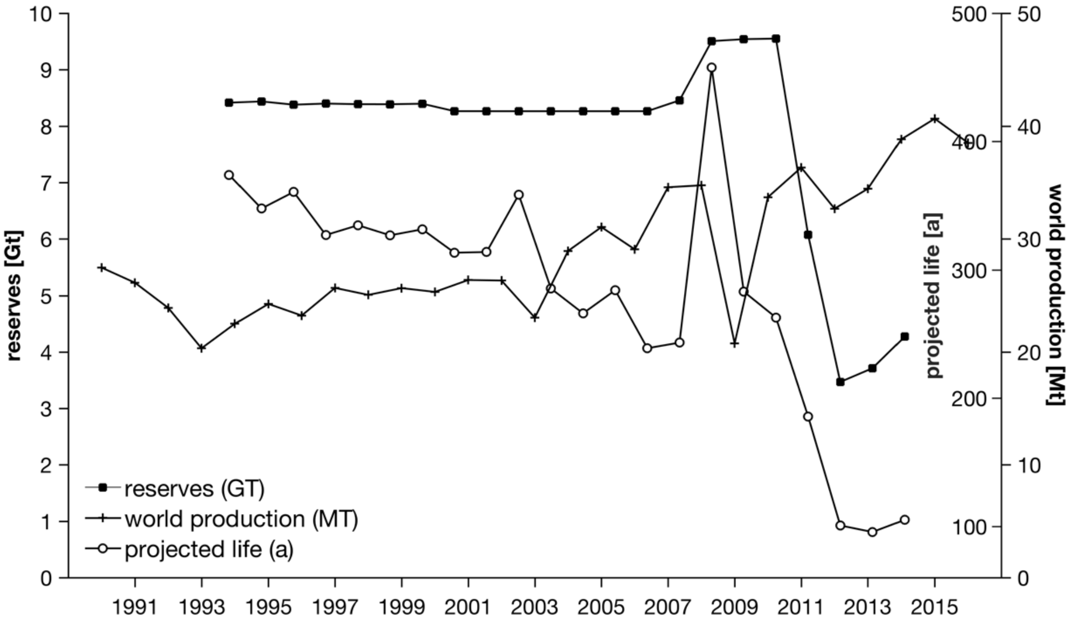

Fig. S1-1 Update of data from Manning (2015), extended by the two most recent years. Data from Jasinski (2017), accessed through https://minerals.usgs.gov/minerals/pubs/commodity/potash/ on 2017-06-13.

S2. Nutrient removal by crop plants

In addition to the data for Miscanthus shown in the main text, we provide here some exemplary additional data on crop plants that would potentially benefit from rock released nutrients (Fig. S2-1). The historical development of crop yields shows that the nutrient extraction of major crops increased steeply in the past (Fig. S2-2) indicating the need for a sustainable long-term nutrient cycle management, not only for new energy plants.

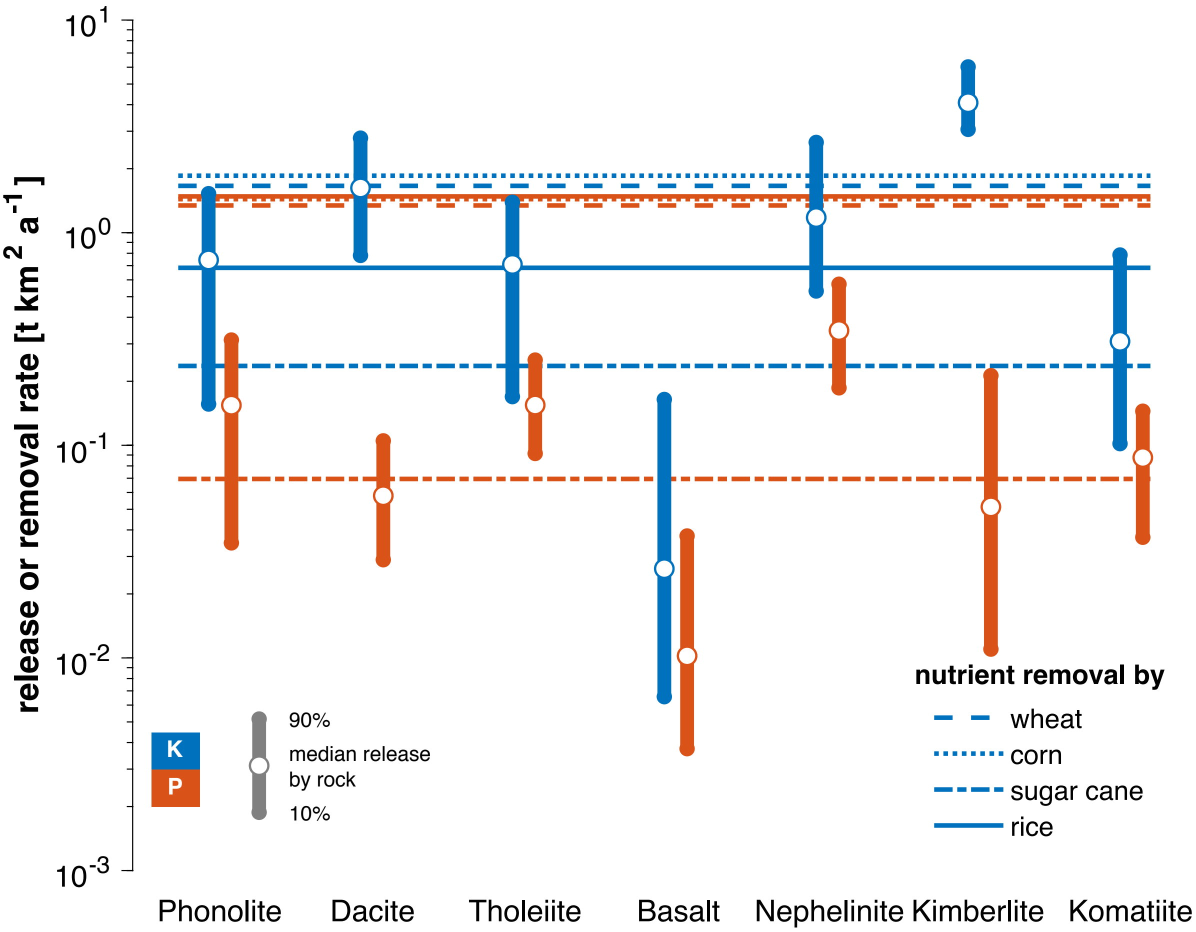

Fig. S2-1 Weathering release rates (circles; bars as variability indicator) of P and K from a few selected volcanic rocks (assuming their full dissolution during a natural weathering scenario based on subtropical Japanese catchments (cf. S6)) in comparison with the average nutrient removal by harvesting the crops (dashed lines), i.e. the actual nutrient removal from the cropland, whereas residues are considered to remain on the land.

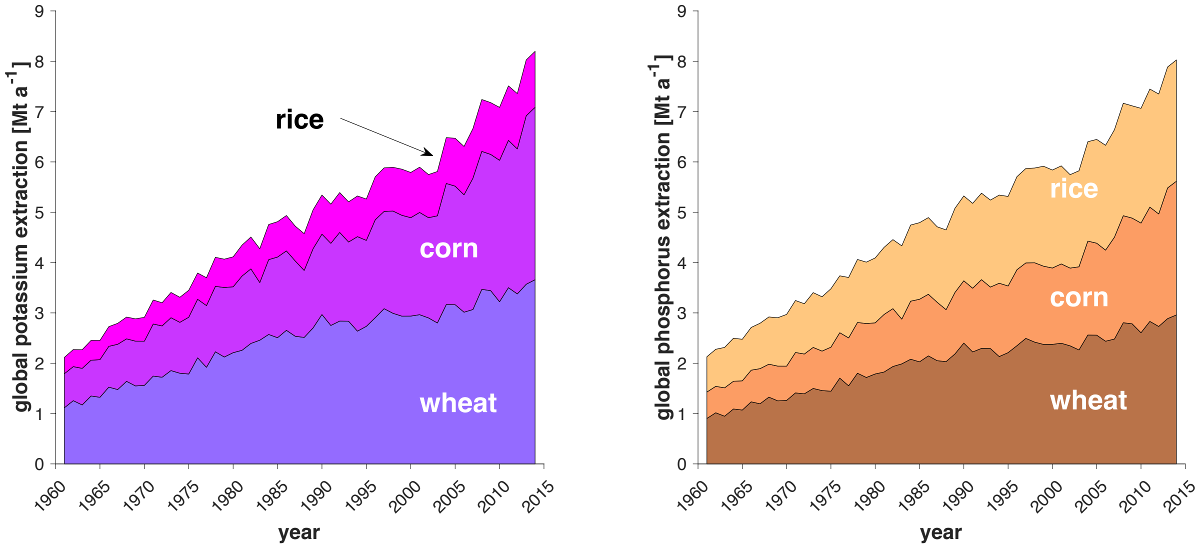

Fig. S2-2 The total annual global removal of K and P by harvest for three major crops over time. Data taken from FAOSTAT (2017).

The removal of nutrients was calculated based on published data on crop yields (Tab. S2-1) and average contents of P and K from the literature in selected crop types (Tab. S2-2), considering only the harvestable material (mainly grains, for sugar cane: stalks, for Miscanthus: all harvestable parts):

$$Nutrient\ removal = \frac{Element\ content\ (\%)}{100} \times Yield \qquad \text{Eq. S2-1}$$

Tab. S2-1 Global average yields of selected crop plants.

Plant	**Yield in 2014 (t km^{-2})**	**Reference**
Barley	292.33	FAOSTAT (2017)
Corn	561.57	FAOSTAT (2017)
Rice	455.69	FAOSTAT (2017)
Soy beans	260.76	FAOSTAT (2017)
Sugar cane	6946.6	FAOSTAT (2017)
Wheat	330.74	FAOSTAT (2017)
	Observed yield min/max (t km^{-2})	
Miscanthus	40/4400	Brosse et al. (2012)

Tab. S2-2 Potassium and phosphorus contents in harvestable parts of plants (grains, stalks), in case of Miscanthus, the value refers to all harvestable parts.

Plant	K (% of biomass)	P (% of biomass)	Reference
Barley	0.009	0.01	Erbs et al. (2010)
Corn	0.33	0.256	Belitz (2009)
Rice	0.15	0.325	Belitz (2009)
Soy beans	2.05	0.67	Batal et al. (2010)
Sugar cane	0.0034	0.001	Fageria (1991)
Wheat	0.502	0.406	Belitz (2009)
Miscanthus min	0.11	0.04	Brosse et al. (2012)
Miscanthus max	1.58	0.11	Brosse et al. (2012)

S3. The underlying database *GEOROC*

The GEOROC data was provided as Microsoft Access database files by the maintainer of http://georoc.mpch-mainz.gwdg.de/georoc/ on 2018-04-11. Files were converted and stored in a MySQL database (v8.0.12) for further queries. The query output was loaded into the software MATLAB (R2018b) to create statistics and figures. Below, a rough rundown of the preparation is given. Fig. S3-1 provides an overview of the geographic distribution of samples included in the calculations.

1. Select the data, that should be used, from the entirety of the database. This creates a table, that has all the chemical data in it, plus some additional information to classify the material and to exclude certain samples (subaquatic, not whole rock…).

```
CREATE TABLE export_dataset
SELECT SAMPLE_NUM, SAMPLE_ID, ROCK_TYPE, ROCK_CLASS, MATERIAL, ITEM_MEASURED, ITEM_TYPE,
VALUE_MEAS, UNIT, LATITUDE_MIN, LATITUDE_MAX, LONGITUDE_MIN, LONGITUDE_MAX, ELEVATION_MIN,
ELEVATION_MAX, LAND_OR_SEA

FROM g_samples

INNER JOIN g_batches ON g_samples.SAMPLE_NUM = g_batches.SAMPLE_NUM
INNER JOIN g_analyses ON g_batches.BATCH_NUM = g_analyses.BATCH_NUM
INNER JOIN g_chemistry ON g_analyses.ANALYSES_NUM = g_chemistry.ANALYSES_NUM
INNER JOIN g_locations ON g_samples.LOCATION_NUM = g_locations.LOCATION_NUM
```

2. The relational style of the data had to be converted to a linear list of samples, each with data on selected parameters (SiO_2, etc.). While doing this, a column was introduced, classifying the samples by SiO_2 content into
   - Ultrabasic rocks, containing < 45 wt% SiO_2, called pu, vu (p: plutonic; v: volcanic)
   - Basic rocks, containing 45 - 52 wt% SiO_2, called pb, vb
   - Intermediate rocks, containing 52.0001 - 63 wt% SiO_2, called pi, vi
   - Acid rocks, containing > 63 wt% SiO_2, called pa, va

```
SELECT SAMPLE_NUM, MATERIAL, LAND_OR_SEA, ROCK_CLASS, ROCK_TYPE,

  CASE WHEN ITEM_MEASURED = 'SIO2' THEN
   (CASE WHEN (VALUE_MEAS < 45 AND ROCK_TYPE='VOL') THEN "vu" ELSE
   (CASE WHEN (VALUE_MEAS < 45 AND ROCK_TYPE='PLU') THEN "pu" ELSE
   (CASE WHEN (VALUE_MEAS < 45 AND ROCK_TYPE='PEG') THEN "pu" ELSE
   (CASE WHEN (VALUE_MEAS between 45 AND 52 AND ROCK_TYPE='VOL') THEN "vb" ELSE
   (CASE WHEN (VALUE_MEAS between 45 AND 52 AND ROCK_TYPE='PLU') THEN "pb" ELSE
   (CASE WHEN (VALUE_MEAS between 45 AND 52 AND ROCK_TYPE='PEG') THEN "pb" ELSE
   (CASE WHEN (VALUE_MEAS between 52.0001 AND 63 AND ROCK_TYPE='VOL') THEN "vi" ELSE
   (CASE WHEN (VALUE_MEAS between 52.0001 AND 63 AND ROCK_TYPE='PLU') THEN "pi" ELSE
   (CASE WHEN (VALUE_MEAS between 52.0001 AND 63 AND ROCK_TYPE='PEG') THEN "pi" ELSE
   (CASE WHEN (VALUE_MEAS > 63 AND ROCK_TYPE='VOL') THEN "va" ELSE
   (CASE WHEN (VALUE_MEAS > 63 AND ROCK_TYPE='PLU') THEN "pa" ELSE
   (CASE WHEN (VALUE_MEAS > 63 AND ROCK_TYPE='PEG') THEN "pa" ELSE NULL END)
      END) END) END) END) END) END) END) END) END) END) END) ELSE NULL END

  AS geochem_class

 , CASE WHEN ITEM_MEASURED = 'SIO2' THEN
       (CASE WHEN VALUE_MEAS < 0 THEN NULL ELSE VALUE_MEAS END) ELSE NULL END AS
       SIO2_wtperc
 , CASE WHEN ITEM_MEASURED = 'P2O5' THEN
       (CASE WHEN VALUE_MEAS < 0 THEN NULL ELSE VALUE_MEAS END) ELSE NULL END AS
       P2O5_wtperc
 , CASE WHEN ITEM_MEASURED = 'K2O' THEN
       (CASE WHEN VALUE_MEAS < 0 THEN NULL ELSE VALUE_MEAS END) ELSE NULL END AS
       K2O_wtperc
 , CASE WHEN ITEM_MEASURED = 'MGO' THEN
```

```sql
        (CASE WHEN VALUE_MEAS < 0 THEN NULL ELSE VALUE_MEAS END) ELSE NULL END AS
        MGO_wtperc
 , CASE WHEN ITEM_MEASURED = 'CAO' THEN
        (CASE WHEN VALUE_MEAS < 0 THEN NULL ELSE VALUE_MEAS END) ELSE NULL END AS
        CAO_wtperc
 , CASE WHEN ITEM_MEASURED = 'NA2O' THEN
        (CASE WHEN VALUE_MEAS < 0 THEN NULL ELSE VALUE_MEAS END) ELSE NULL END AS
        NA2O_wtperc
 , CASE WHEN ITEM_MEASURED = 'NIO' THEN
        (CASE WHEN VALUE_MEAS < 0 THEN NULL ELSE VALUE_MEAS END) ELSE NULL END AS
        NIO_wtperc
 , CASE WHEN ITEM_MEASURED = 'CR2O3' THEN
        (CASE WHEN VALUE_MEAS < 0 THEN NULL ELSE VALUE_MEAS END) ELSE NULL END AS
        CR2O3_wtperc
 , CASE WHEN ITEM_MEASURED = 'SI' THEN
        (CASE WHEN VALUE_MEAS < 0 THEN NULL ELSE VALUE_MEAS END) ELSE NULL END AS
        SI_PPM
 , CASE WHEN ITEM_MEASURED = 'K' THEN
        (CASE WHEN VALUE_MEAS < 0 THEN NULL ELSE VALUE_MEAS END) ELSE NULL END AS
        K_PPM
 , CASE WHEN ITEM_MEASURED = 'CA' THEN
        (CASE WHEN VALUE_MEAS < 0 THEN NULL ELSE VALUE_MEAS END) ELSE NULL END AS
        CA_PPM
 , CASE WHEN ITEM_MEASURED = 'MG' THEN
        (CASE WHEN VALUE_MEAS < 0 THEN NULL ELSE VALUE_MEAS END) ELSE NULL END AS
        MG_PPM
 , CASE WHEN ITEM_MEASURED = 'NA' THEN
        (CASE WHEN VALUE_MEAS < 0 THEN NULL ELSE VALUE_MEAS END) ELSE NULL END AS
        NA_PPM
 , CASE WHEN ITEM_MEASURED = 'P' THEN
        (CASE WHEN VALUE_MEAS < 0 THEN NULL ELSE VALUE_MEAS END) ELSE NULL END AS
        P_PPM
 , CASE WHEN ITEM_MEASURED = 'NI' THEN
        (CASE WHEN VALUE_MEAS < 0 THEN NULL ELSE VALUE_MEAS END) ELSE NULL END AS
        NI_PPM
 , CASE WHEN ITEM_MEASURED = 'CR' THEN
        (CASE WHEN VALUE_MEAS < 0 THEN NULL ELSE VALUE_MEAS END) ELSE NULL END AS
        CR_PPM

FROM export_dataset

WHERE (ITEM_MEASURED IN
        ('SIO2', 'K2O', 'P2O5','CAO','MGO','NA2O', 'NIO', 'CR2O3', 'SI', 'K','CA',
         'MG','NA', 'P', 'NI', 'CR'))

AND MATERIAL = 'WR'
AND (ROCK_TYPE = 'VOL' OR ROCK_TYPE = 'PLU' OR ROCK_TYPE = 'PEG')
AND LAND_OR_SEA="SAE"

GROUP BY SAMPLE_NUM
```

3. A table was exported from MySQL and imported to MATLAB. The data contained SiO_2, K_2O, P_2O_5, NiO, Cr_2O_3, Si, K, P, Ni, Cr.
It was narrowed down to contain only rock samples of plutonic, pegmatitic, and volcanic nature. Only under subaerial conditions and only analyses were selected where the whole rock was analysed. As there were very few data points with negative values, the code was adapted not to include those values.

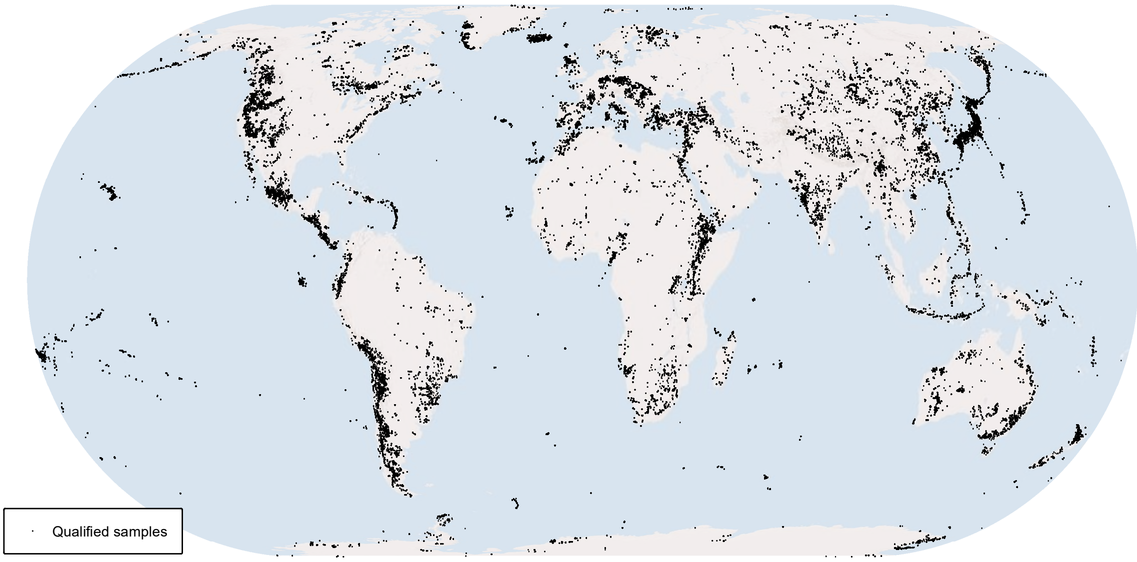

Fig. S3-1 Global distribution of qualified samples in the GEOROC database.

S4. CO_2 capture potential

The ability to sequester atmospheric CO_2 is rock specific and depends on the cations that can be released during hydrolysis. It is defined as the carbon dioxide removal potential R_{CO2} in tonnes CO_2 per tonne of rock:

$$R_{CO_2} = \frac{M_{CO_2} * \sum(2n_{Ca^{2+}}, 2n_{Mg^{2+}}, n_{K^+}, n_{Na^+})}{1000} * \omega \qquad \text{Eq. S3-1}$$

n = molar amount of cation x, M_{CO2} = molar mass of CO_2, and ω = 0.85, factoring in seawater equilibration processes (cf. Fig. 1 in Renforth et al., 2013). They considered only divalent cations, where two charges bind about 1.7 moles CO_2 (~15% less, thus factor 0.85). Fig. 2 in the main text shows only selected rock types. Fig. S3-1 provides an overview over R_{CO2} values of all volcanic rock types differentiated in the GEOROC database. Plutonic rock types were omitted here, since the amount of data on particular rock types in the provided data is comparably low. Additionally, the data pre-processing to get “clean” rock types, is very work intensive, which is not justified in the context of this publication.

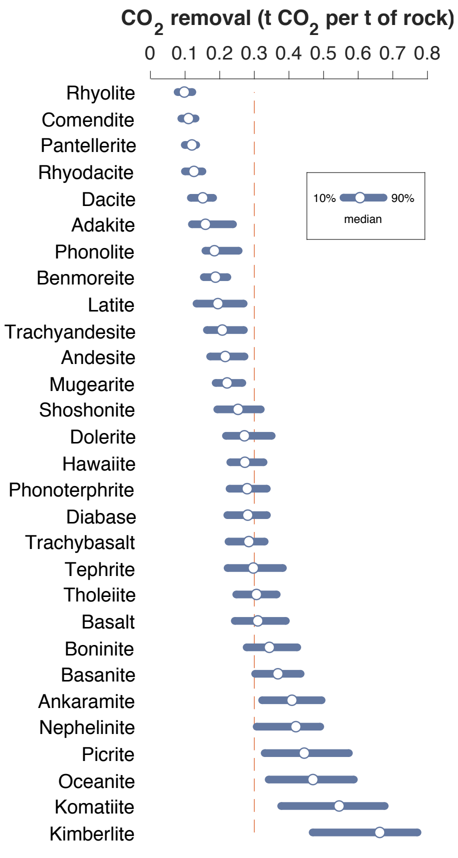

Fig. S 4-1 Calculated efficiency of CO_2 removal (R_{CO2}) for all volcanic rock types given in the GEOROC database. The dashed line is the pessimistic CO_2 emission during production of rock flour from Moosdorf et al. (2014), but would be lower fossil energy provides were provided by renewables for the processing.

S5. Global distribution of rock classes

The distribution of rock classes gives a rough overview of where to find the respective rock class. This overview is based on data from the global lithological map database GLiM (Hartmann and Moosdorf, 2012) with an average scale of 1:3,750,000, therefore local to regional scale occurrences may be under-represented.

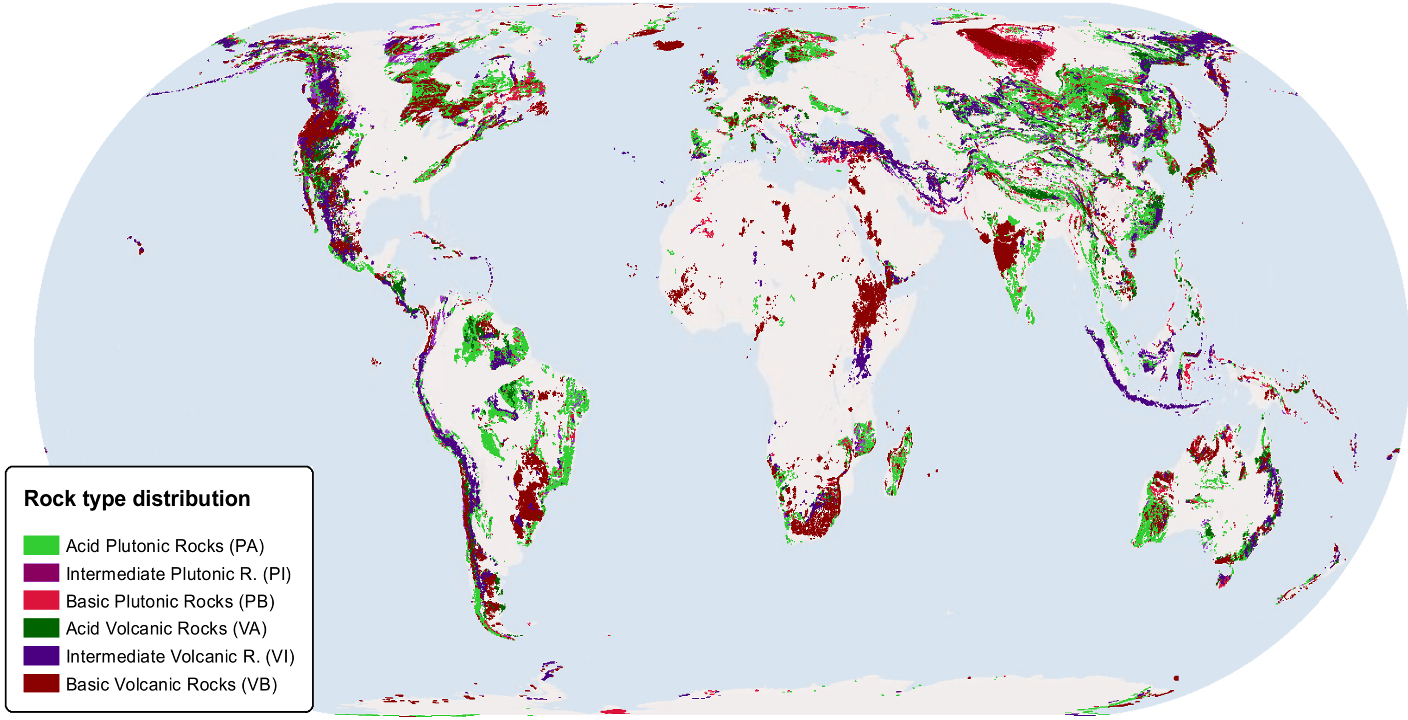

Fig. S5-1 Global overview of the rock classes considered in this study. Data was extracted from the global lithological map database GLiM (Hartmann and Moosdorf, 2012). Coverage may appear larger than actual observations due to scaling effects for the figure.

Tab. S5-1 Areal extents of the mapped rock classes

Rock class	Total area [10^6 km^2]	land surface cover [%]
pa	8.58	5,8%
pb	1.03	0,7%
pi	0.58	0,4%
va	1.54	1,0%
vb	5.25	3,5%
vi	2.59	1,7%

S6. Calculation of element release rates

To compare potential element release differences between rock classes based on their relative rate of weathering and the relative composition of rock geochemistry, bulk weathering rates for a well-studied humid subtropical region (the Japanese Archipelago) comparable to areas of likely application are chosen (Hartmann and Moosdorf, 2011;Hartmann et al., 2013). The Japanese Archipelago is in general characterized by high weathering capacity in comparison to humid tropical areas with depleted weathering profiles, where weathering rates can decrease by about 90% (Hartmann et al., 2014). For catchments that were dominated by basic and intermediate volcanic rocks, a weathering rate of 33 t base cations + Si km^{-2} a^{-1} was observed based on the analysis of nearly 400 catchments (Hartmann and Moosdorf, 2011). Field experiments with direct measurements of enhanced weathering rates due to finely ground rock product application, which would allow a more precise upscaling are still missing. The highest observed weathering rates of volcanic rocks including large areas of pyroclastics (comparable in some sense with EW) are about 3.5 times higher than rates calculated from Japanese catchments (Schopka et al., 2011). However, the temperature effect makes up for a about a factor of two alone if the temperature difference between Japan and the Philippines are considered. Data from the latter study consider also the significant contribution of waters with higher residence time than expected in top soil treated by rock powder, which affects the overall dissolution rate of total rock compartment including the soils (Maher, 2011).

The P and K release rate by enhanced chemical weathering is calculated assuming that P and K are released at the same relative rate as major cations and silicon are released via weathering, as a first order estimate (Hartmann and Moosdorf, 2011) for each considered rock type and its reported geochemical composition using the data from the GEOROC database (Suppl. S2). As P and K are preferentially taken up by the ecosystems the calculation, the assumptions are considered to be conservative, until field experimental data are available.

The first order upper boundary element release rate is calculated based on the major cation and silicon release rate and proportional to the total rock mass and assuming full dissolution as:

$$\frac{W_R}{\sum(\%Cations + Si)_{sample}} \times c_{element} = element\ release\ rate\ [t\ km^{-2} a^{-1}] \qquad \textit{Eq. S4-1}$$

With W_R as the spatially explicit weathering rate (here 33 t base cations and Si km^{-2} a^{-1}) and *%Cations* as the rock specific values. This approach is suitable for geogenic nutrients like P and K. Elemental solubility, pH and redox processes directly affect the release and retention of trace metals like Cr or Ni, which is discussed separately.

S7. Rock class statistics

Based on the procedure described in section S2, data for the figures of the main text were produced. A more detailed overview on the basic statistics of the specified geochemical rock classes and distinct rock types, for Cr, Ni, P, and K, is given below in Tabs. S7-1 – S7-4.

Tab. S7-1 Basic statistics of the data for chromium, extracted from the GEOROC database. All values given in ppm.

	type	median	mean	std	min	max	10%ile	90%ile	n
	basalt	140	226	340	0	21,509	19	475	49,942
	dunite	2,651	3,596	6,874	49	80,354	1,350	5,070	137
volcanic	ultrab.	374	713	938	0	21,509	50	1,867	12,932
	basic	180	326	528	0	11,000	24	687	48,681
	Interm.	45	116	236	0	7,301	5	275	37,907
	acid	8	33	153	0	7,018	0	64	18,669
plutonic	ultrab.	194	1,046	3,460	0	109,303	3	2,850	3,216
	basic	159	423	779	0	17,745	17	1090	4,885
	Interm.	47	166	424	0	7,,345	3	389	3,020
	acid	13	37	137	0	4,621	0	88	2,969

Tab. S7-2 Basic statistics of the data for nickel, extracted from the GEOROC database. All values given in ppm.

	type	median	mean	std	min	max	10%ile	90%ile	n
	basalt	74	110	151	0	8,550	13	231	52,091
	dunite	2,129	2,985	5,743	320	50,669	916	3,354	236
volcanic	ultrab.	227	462	693	0	24,591	44	1,256	13,471
	basic	89	161	393	0	55,743	20	299	50,652
	Interm.	24	51	121	0	7,900	3	118	39,830
	acid	5	13	35	0	1,734	0	29	18,324
plutonic	ultrab.	157	600	920	0	14,182	6	1,966	3,331
	basic	91	192	365	0	8,667	18	410	5,043
	Interm.	24	59	110	0	2,,031	2	146	3,118
	acid	6	15	53	0	1171	0	29	3,355

Tab. S7-3 Basic statistics of the data for potassium, extracted from the GEOROC database. All values given in ppm.

	type	median	mean	std	min	max	10%ile	90%ile	n
	basalt	7,803	9,440	7,982	0	456,581	1,826	18,429	68,846
	dunite	83	898	7,139	0	95,384	0	830	184
volcanic	ultrab.	9,381	11,333	10,673	0	86,335	772	22,082	20,697
	basic	6,724	9,920	11,332	0	340,360	1,245	20,090	70,155
	Interm.	13,531	18,590	16,262	0	456,581	4,317	43,085	59,515
	acid	30,451	29,966	13,656	0	123,858	12,120	45,492	32,785
plutonic	ultrab.	2,158	7,382	11,117	0	148,513	83	22,165	4,774
	basic	4,898	9,326	12,234	0	102,938	664	24,157	6,471
	Interm.	16,686	22,249	18,570	0	152,830	3,819	47,650	4,680
	acid	31,463	30,257	12,814	0	128,175	13,282	44,662	6,207

Tab. S7-4 Basic statistics of the data for phosphorus, extracted from the GEOROC database. All values given in ppm.

	type	median	mean	std	min	max	10%ile	90%ile	n
	basalt	1,309	1,609	1,248	0	31,728	428	3,186	65,363
	dunite	52	476	4,560	0	59,702	0	305	171
volcanic	ultrab.	2,589	2,982	3,827	0	366,594	436	5,412	20,298
	basic	1,309	1,654	1,344	0	24,309	367	3,360	67,737
	Interm.	916	1,173	978	0	39,540	393	2,226	56,786
	acid	393	493	504	0	18,286	75	1,004	31,195
plutonic	ultrab.	969	4,482	11,252	0	238,591	44	11,434	4,655
	basic	698	1,260	2,356	0	139,655	105	3,055	6,254
	Interm.	890	1,229	1,201	0	26,185	262	2,619	4,461
	acid	428	500	504	0	19,639	87	960	5,876

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