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# Glacially abraded rock flour from Greenland: Potential for macronutrient supply to plants

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## Abstract

Rock flour (RF) is a fine-grained material produced naturally by glacial movement and resulting bedrock abrasion. In Greenland fluvial transported RF from the inland ice sheet sediments in riverbeds and marine outflows. This fine-sized RF (50% < 9.8 μm) has a high reactivity and may therefore potentially be used to rejuvenate nutrient poor soils and provide nutrients to plants. The aim of this study was to evaluate the ability of a RF from Greenland to supply P, K, Mg, and S to plants. A double-pot system was used, in which ryegrass (*Lolium perenne L.*) could take up nutrients from both a hydroponic solution and a soil-compartment with or without RF amendment; a soil mixture or pure sand was used in the soil-compartment to estimate RF-soil interaction effects. Omission of single nutrients from the hydroponic solution allowed assessment of which nutrients the RF in the soil-compartment was able to supply. Ryegrass biomass was harvested four times during 62 days. We found that RF could supply K continuously to plants grown in soil or sand, but insufficient to fully circumvent K deficiency. During 62 days 5.8% and 4.3% of the applied K from RF was accumulated in the aboveground plant tissue in soil and sand, respectively. Mg was supplied from RF to plants in sand, but no significant effects were observed in soil, possibly due to background soil Mg availability. The amounts of P and S supplied to plants were insignificant. These results indicate the potential of Greenland RF to act as a slow release K and Mg fertilizer.

**Key words:** alternative fertilizer / double-pot / mineral fertilizer / potassium / rock dust / rock powder

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## 1 Introduction

In agricultural systems recurrent harvests continuously remove nutrients from the soil. To preserve soil fertility and maintain substantial yields, nutrients need to be replenished. In modern, conventional systems this is typically done by applying mineral fertilizers derived from industrial fixation of atmospheric nitrogen and extracts of rock minerals. Crushed rocks have been suggested as a cheap alternative to fertilize nutrient poor and structurally disarmed soils (*Leonardos* et al., 1987; *Coroneos* et al., 1995; *Van Straaten*, 2002; *Manning*, 2015; *Basak* et al., 2018). The idea of using crushed stones as a nutrient input dates back to the 19$^{th}$ century (*Magnus*, 1850; *Hensel*, 1894). Through surface weathering, rocks can release essential plant macronutrients such as potassium (K), magnesium (Mg), sulfur (S), phosphorus (P), and calcium (Ca).

Glacially abraded rocks could potentially be a relevant alternative source of mineral nutrients. Glaciers serve as natural grinders as they move through landscapes. The fine abraded rocks are fluvially transported in meltwater and deposited in either lakes or oceans, creating large areas with rock flour (RF) deposits. In the Northern Hemisphere, much of the fertile land is found in the periglacial zone of past ice ages (*Rosing*, 2016). The Greenland Ice Sheet is the only remaining ice sheet on the Northern Hemisphere and around Greenland vast amounts of RF are found. The Greenlandic bedrock is dominated by granitic gneisses with subordinate metasedimentary, mafic and ultramafic domains. The blanket erosion of the basement and mixing of the debris through meltwater transport and ice dynamics integrates erosion products from very large areas of the basement (*Bartholomew* et al., 2011). The Greenlandic RF is well-mixed in terms of provenance and, thus, bulk chemical composition, though it is subsequently differentiated to some extent during fluvial transport in the proglacial environment. The fine fraction, which is the source of the RF used in the present study, is geochemically close to average upper continental crust (*Rudnick* and *Gao*, 2003) but slightly depleted in $SiO_2$ and CaO, and slightly enriched (by 1.5 to 2 times) in $K_2O$. This is probably mostly due to selective deposition of quartz with the sand fraction in the fluviatile system, while the silt and clay-sized fractions are enriched in mica which settled in the marine or lacustrine deltas. *Bendixen* et al. (2019) estimate the annual sediment load from the Greenlandic ice sheet to be 0.89 Gt $y^{-1}$. Warmer

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climates in the future will continue to give increased sediment loads (*Parizek* and *Alley*, 2004; *Overeem* et al., 2017; *Van As* et al., 2018), so as a resource Greenlandic RF is vastly abundant (*Bendixen* et al., 2019). *Hasholt* et al. (2012) found that 98% of deposited RF in Greenland had a particle size < 63 μm in years where deposition was not unusually high. To our knowledge, no scientific studies have been published on using glacial RF to enhance soil fertility.

Greenlandic RF contains macronutrients: Ca, K, Mg, small amounts of P and S, and no nitrogen (N) (Tab. 1). RF and sediment loads in general from the Greenlandic ice sheet are major contributors to oceanic Si and P (*Hawkings* et al., 2016, 2017). The sedimentation of RF occurs in distinct particle size zones depending on water movement. In the material used here, 50% of the material had a particle size < 9.8 μm and the size range was < 0.08–112 μm. It is likely that weathering and direct solubilisation of RF will occur at accelerated rates by introduction of RF to warmer climates. This can potentially enhance the fertility of soil under agricultural production systems where the availability of mineral nutrients is low.

The release of nutrients from rocks mainly depends on the mineralogy of the material, the surface area of the rock materials being applied (*Lasaga* et al., 1994; *Harley* and *Gilkes*, 2000; *Basak* et al., 2018), and the geo-biochemical conditions of the soil environment. *Blum* et al. (1989) argue that mineralogy is less important when using low grade rocks, where > 70% is usually oxygen bound to Si, Fe or Al. They argue that grinding intensity is a greater determinant of the rock powder's performance as fertilizers. For artificially ground rock powders, increasing grinding intensity is associated with increased costs and energy use. According to Rittinger's theory, the amount of energy required to crush a rock is proportional to the new surface area created upon crushing (*Guimaraes* et al., 2007). The potential of using existing waste or by-products from quarries as low-cost soil amendments has been investigated by many (*Bakken* et al., 1996; *Bolland* and *Baker*, 2000; *Gillman* et al., 2002; *Fyfe* et al., 2006; *Van Straaten*, 2006; *Silva* et al., 2014; *Ramos* et al., 2017; *Basak* et al., 2018). *Silva* et al. (2014) evaluated K supply to rice from six different rocks crushed to different particle sizes and found that, when applied to soil, the material with the finest particle size (22.14% > 1 mm and 20.44% < 125 μm) had the greatest effect on rice yield as well as on K, Ca, and P uptake. The crushed rock material was composed mainly of ferromagnesian minerals and originated as a by-product from an emerald mine in Brazil (*Silva* et al., 2012, 2014). However, none of these materials were as fine-grained as Greenlandic RF, which is an unprocessed, naturally occurring material with no energy requirement for reducing particle size further. Compared to native rocks from areas with intensified agriculture, such as the ground rocks used in the studies above, the Greenlandic RF may be more reactive as it is deposited in an Arctic environment, where weathering occurs slower. The rate of deposition of rock flour is often very high, such that deposits are rapidly sealed from the environment by subsequent deposition. The RF studied here was collected at a fossil deposit with discontinuous permafrost (*Westermann* et al., 2015). Fossil deposits have thus experienced temperatures close to freezing since deposition up to 8 K-year ago (*Lecavalier* et al., 2014). This may explain the very limited weathering or recrystallization experienced in fossil deposits, despite the intrinsic high reactivity of the rock flour (*Rosing* et al., 2018). X-ray powder diffraction analysis shows that fossil and recent deposits are both vastly dominated by the main rock forming minerals of the basement hinterland, feldspar, quartz, biotite, hornblende, and pyroxene (*Rosing* et al., 2018).

Even though amending rock materials can enrich the soil, plants will only benefit from it if the nutrients released remain available for plant uptake in the soil. This greatly depends on soil properties such as pH, water content, specific surface area, cation exchange capacity (CEC), base cation saturation, as well as root exudation, microbiology, and other biological processes in the soil. Another interaction could be ion exchange both where ions from RF adsorb to soil, where soil-bound plant nutrients are released from soil due to exchange with other ions released from the amended minerals. Even though very little P is found in Greenlandic RF, release of other solutes such as silica may cause ion exchange with phosphate adsorbed on soil particles, which may then result in enhanced soil P availability for plants (*Brown* and *Mahler*, 1989; *Puppe* and *Sommer*, 2018). *Pati* et al. (2016) showed that fertilization with diatomaceous earth containing 63.7% silicon dioxide in a field trial, enhanced rice P and K acquisition as compared to where no diatomaceous earth was applied, and nutrient additions were otherwise the same.

The overall objective of this study was to determine whether Greenlandic RF can supply essential macronutrients to plants. It was hypothesised that: (1) RF can supply each of the macronutrients P, K, Mg and S to plants, and sustain the potential maximum yield (PMY) obtained when all essential nutrients (including N) are supplied in sufficient quantities, and (2) plant uptake of P, and possibly other nutrients, may be enhanced by release from the native soil pool upon RF addition, due to the exchange of ions with the soil surfaces. An experimental double-pot setup designed to isolate the effect of individual nutrients was used (first hypothesis) and the nutrient supply to ryegrass was tested in both soil and pure sand, where particle surfaces are considered inert thus will not be subject to ion exchange in any form (second hypothesis).

## 2 Methods

### 2.1 Rock flour, soil, and sand

Greenlandic RF was acquired within the Archean Block of West Greenland, which is dominated by Tonalite-Trondhjemite-Granodiorite gneisses. The RF was collected in July 2015 from a raised seabed at Maalutu (64°17′N, 51°43′W), 15 km North of Nuuk in Greenland. The original depositional environment was marine and the site of deposition would have been close to the main body of the Greenland ice sheet at the time of deposition (*Lecavalier* et al., 2014). Since then, the ice has retreated and the deposit has experienced isostatic uplift, such that the top of the deposit is located ca. 13 m above present sea level (*Christiansen*, 2003). The mineralogical composition of RF from the same locality as that used in our experiment was determined by XRD: quartz: 22%, plagioclase: 40%, K-feldspar: 13%, amphibolite: 11%, clinopyroxene: 3%, and mica (mainly biotite): 11% (*Christiansen*, 2003). Given the mineralogical and chemical composition of the RF, biotite would be the most reactive phase and the most likely source of K, Mg, $Fe^{2+}$, and Si in the short term, while feldspars and amphibole would be the dominant source of Ca. Although a significant mass fraction of the RF is $< 1\ \mu m$, clay minerals are not present in significant amounts (*Sarkar* et al., 2018).

The material was dried at 60°C and stored at room temperature until use. Chemical analysis was performed by the Centre de Recherches Pétrographiques et Géochimiques (CRPG) at the French National Centre for Scientific Research (CNRS) in Nancy, France, according to *Carignan* et al. (2007). Particle size was analyzed with Laser Particle Sizer with a measuring range of 0.08–2000.00 μm by FRITSCH GmbH, Milling and Sizing, Idar-Oberstein, Germany. Chemical composition, pH and information about particle size are found in Tab. 1.

Soil was collected from the CRUCIAL long-term field trial at the University of Copenhagen's Experimental Farm (55°40′N, 12°18′E) in July 2015. The soil was sandy loam, and samples were taken from a treatment that had received no mineral fertilizer for the past 15 years and had been in an arable rotation of crops. Soil properties and nutrient availability are found in Tab. 2. Olsen-P and exchangeable K and Mg were analysed by OK Laboratorium for Jordbrug, Viborg, Denmark, according to Danish Standard (*Sørensen* and *Bülow-Olsen*, 1994). The soil was air-dried and sieved at 4 mm. At setup the soil was mixed with sand 1 : 1 in a mixer. This was done to mitigate soil compaction, improve water infiltration, and improve overall soil structure. These treatments are referred to as soil mixture treatments.

The quartz sand was purchased from Dansand Silkeborg A/S and had a grain size of 0.4–0.9 mm. Grain size as well as chemical analysis were analysed by the supplier; chemical composition can be seen in Tab. 2. Two days before planting, both the soil mixture and sand were wetted to 40% water-holding capacity (WHC) and after planting this was raised to 60% WHC and kept so throughout the experiment. The WHC was determined in 200 mm long PVC cylinders of a diameter of 40 mm with a drainage time of 24 hours on a sandbed, performed according to ISO14238 (*Margesin* and *Schinner*, 2005). This was measured in both sand and soil mixture with 0, 5, and 10% RF addition. RF was homogeneously mixed into the sand or soil mixture by thorough shaking in a plastic bag for each pot individually at day 0. The soil mixture not receiving RF was also shaken to ensure the same treatment.

**Table 1**: Chemical and physical properties of the RF.

| **Rock flour from Maalutu** | |
|---|---|
| $pH_{water}$ | 8.3 |
| $P_2O_5$ | 1.1 mg $g^{-1}$ |
| $K_2O$ | 28.7 mg $g^{-1}$ |
| MgO | 26.4 mg $g^{-1}$ |
| S | 1 mg $g^{-1}$ |
| CaO | 37.1 mg $g^{-1}$ |
| $Fe_2O_3$ | 52.0 mg $g^{-1}$ |
| MnO | 7 mg $g^{-1}$ |
| Cl | 0.335 mg $g^{-1}$ |
| $SiO_2$ | 627.6 mg $g^{-1}$ |
| $Al_2O_3$ | 157.1 mg $g^{-1}$ |
| $Na_2O$ | 38.1 mg $g^{-1}$ |
| $TiO_2$ | 4.9 mg $g^{-1}$ |
| Particle size: | |
| 50% of particles | < 9.8 μm |
| 90% of particles | < 40.8 μm |
| Surface area | 0.52 $m^{-2}$ $g^{-1}$ |

**Table 2**: Main soil and sand properties.[a]

| | **Soil** | **Sand** |
|---|---|---|
| $pH_{water}$ | 7.2 ± 0.2 | n.a. |
| Water-extractable P (mg $kg^{-1}$) | 2.9 ± 0.3 | n.a. |
| Olsen-P* (mg $kg^{-1}$) | 7 | n.a. |
| Exchangeable K* (mg $kg^{-1}$) | 85 | n.a. |
| Exchangeable Mg* (mg $kg^{-1}$) | 59 | n.a. |
| Total P (mg $kg^{-1}$) | 430 ± 11.1 | 0 |
| Total C (g $kg^{-1}$) | 20 ± 0.1 | 0 |
| Total N (mg $kg^{-1}$) | 14.6 ± 0.16 | 0 |
| Sand (%) | 65 | 100 |
| Silt (%) | 16 | 0 |
| Clay (%) | 16 | 0 |
| $K_2O$ (%) | n.a. | 0.19 |
| $SiO_2$ (%) | n.a. | 99.40 |
| $Al_2O_3$ (%) | n.a. | 0.32 |

[a]n.a.: analysis not available; *: range of soil nutrient availability indexes considered sufficient for the majority of arable crops: Olsen-P 20–40, exch.-K 70–100, exch.-Mg 40–80 mg $kg^{-1}$.

## 2.2 Double-pot systems

Double-pot systems (*Janssen*, 1974, 1990; *Antil* et al., 2009) grown with perennial ryegrass (*Lolium perenne L.*) were used to evaluate macronutrient supply by RF. The double-pot system relies on Liebig's law of the minimum, where plant growth is limited by the scarcest available nutrient. The system allows plants to take up nutrients from both a soil compartment in a pot and from hydroponic solution containing ample nutrients for optimal plant growth. In the hydroponic solutions, either P, K, Mg, S or nothing (control) was omitted, thus, the plants relied solely on the soil compartment for supply of that nutrient (Fig. 1). In this setup the traditional double-pot system was slightly modified as 10 pots grew into the same hydroponic solution. A similar modification was also used by *Antil* et al. (2009). Ten double-pot systems were set up with 10 pots in each whereof half were amended with 5% RF w : w (34 g) and the other half without, resulting in five replicates and 100 pots in total. The RF application rate corresponded to 30 t $ha^{-1}$ when calculated on the basis of pot surface area (113.1 $cm^2$). As plants grew out of the bottoms of the pots the application rate conversion to t $ha^{-1}$ should be regarded with caution as growth conditions were far from real field conditions. In half the systems, the upper pots (0.62 L) were filled with 600 g soil mixture, while in the remaining systems the pots were filled with sand. At seeding, 0.6 g perennial ryegrass seeds were mixed with 80 g of either soil mixture or sand, and this seedbed mixture was placed on top of the 600 g soil mixture or sand at day 0. A stainless steel mesh (3 mm mesh size) was located on the bottom of each pot to allow root penetration. A small air gap of approximately 1 cm between the mesh in the bottom of the pots, and the surface of the hydroponic solution ensured no exchange of water between the two compartments.

The hydroponics consisted of 55 L nutrient solution with all nutrients (positive control) or omission of P, K, Mg or S. Nutrient solutions were made up of individual stock solutions [revised after *Janssen* (1974); adobted from *Cardoso* et al. (2004)]. The final concentrations in the solutions were 1.5 mM Ca, 7 mM N, 4 mM K, 2 mM P, 0.75–1.25 mM Mg, 0.75 mM S, 2.02 mM Cl, 0.11 mM Fe, 0.05 mM B, 0.1 mM Mn, 0.0008 mM Zn, 0.0006 mM Cu, and 0.0002 mM Mo. Solutions were adjusted to pH 6.5 every three days, constantly aerated and exchanged weekly. At day 20, water samples were taken from hydroponics just before renewing the nutrient solutions. Water samples were analysed with inductively coupled plasma optical emission spectrometry (ICP-OES, Optima 5300 DV, Perkin Elmer, Ontario, Canada) to ensure that nutrient concentrations were adequate and had not been exhausted during seven days' growth. The experiment was performed in January-March in a greenhouse at 18/15°C (day/night) with a 16/8 h light cycle. Pots were watered daily with double deionised water. On a weekly basis all the pots were weighed, and watered separately according to weight. The pots were rotated within the double-pot system every three days to avoid any spatial bias of results.

### 2.3 Harvest and analysis

At day 19, 34, and 52, aboveground biomass (AGB) was cut to a grass height of 6 cm. At day 62, AGB was cut at the soil surface and the root biomass in the pot and hydroponic solution harvested separately. All biomass was dried at 65°C for 72 h and the dry weight recorded.

Dry AGB was ground using a zirconium ball mill. Inter-pot variance was very low due to many plants growing in each pot and therefore a decision was taken to reduce the number of pots used for chemical analyses. Three out of five pot replicates for each treatment were selected randomly by computer software and nutrient composition in AGB analysed. Plant material from each harvest day was digested by adding 70% $HNO_3$ and 15% $H_2O_2$ before analysis by ICP-OES. As no differences on AGB with or without RF were observed in the P-omitted treatments and the Mg-omitted treatment in the soil mixture, it was decided to pool AGB across the harvest dates, according to weight of each harvest, and the pooled sample was analysed in the same way as the other samples.

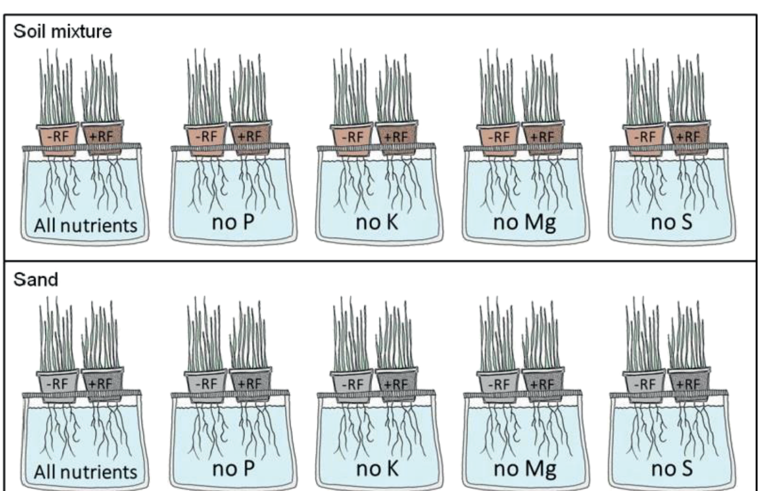


**Figure 1:** Illustration of the double-pot system and treatments used. Ryegrass roots took up nutrients from the top compartment (soil mixture or sand) as well as the hydroponic compartment below. When one nutrient was omitted from the hydroponic solution, plants relied only on the top compartment for supply of that nutrient. Half of the pots received RF. Ten pots (2 treatments and 5 replicates) grew into each hydroponic solution.

### 2.4 Statistics

Accumulated dry biomass (AGB) weights for all treatments in either the soil mixture or sand were compared using one-way ANOVA on log-transformed data as the data were not normally distributed. The same analysis was performed on each individual harvest date (not shown in the graphs). The AGB element concentrations were analysed using one-way ANOVA on non-transformed data as the datasets had a normal distribution. All statistical analyses were performed in SigmaPlot 13.0 Systat software.

## 3 Results

Clear overall differences in ryegrass biomass productivity between the treatments could already be observed in the early stages (Fig. 2). It was found that RF could provide K to plants and Mg was supplied to plants from RF when grown in sand. Amount of harvested AGB increased with each harvest in all treatments. Generally, the plants produced more biomass in the soil mixture than in the sand. Ryegrass supplied with all nutrients pro-

 

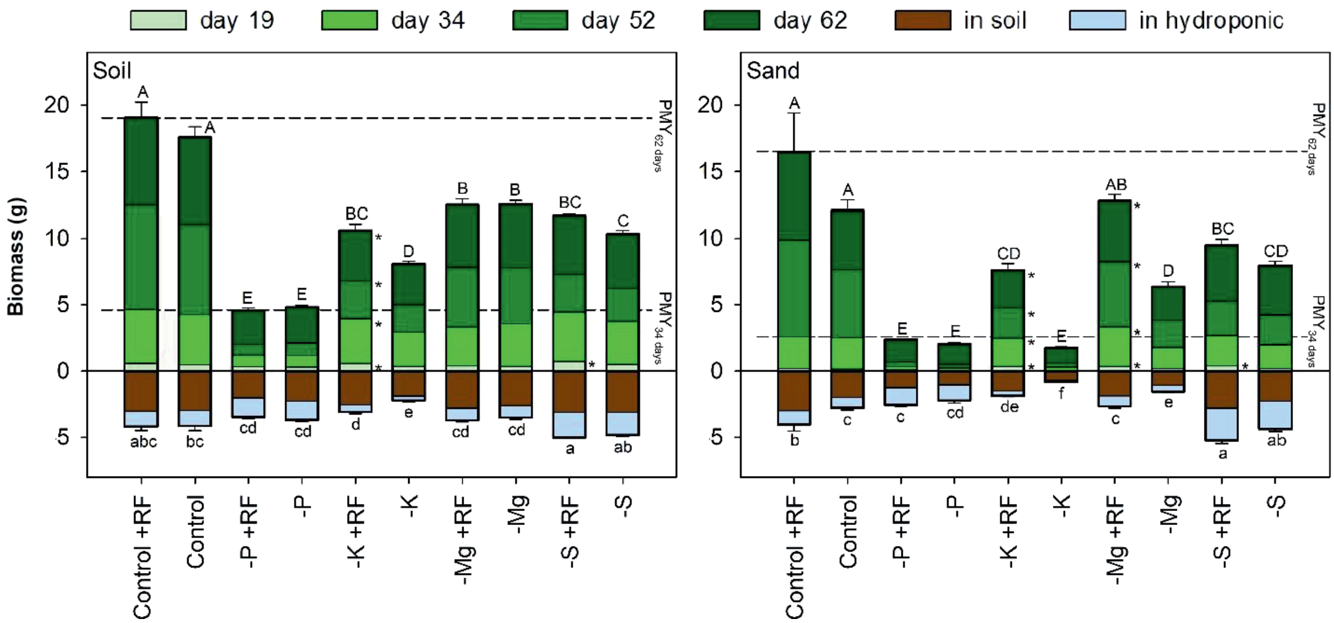


**Figure 2:** Harvested ryegrass aboveground biomass (depicted in green, above zero) at day 19, 34, 52, and 62, and root biomass (depicted by absolute values below zero) in soil and hydroponic solution harvested at 62 days. Plants grown in either soil mixture (1 : 1, soil : sand) or sand in double-pot systems where rock flour (RF) was the only source of the otherwise omitted nutrient in the nutrient solution. Potential maximum yield (PMY) indicates the highest yielded biomasses at day 34 and day 62 in the positive control treatment. Capital letters indicate differences in accumulated aboveground biomass ($p < 0.05$) and small letters indicate differences in accumulated root biomass. Stars indicate a significant effect ($p < 0.05$) of RF on the specific harvest date compared to where no RF is added within the same hydroponic solution. Error bars indicate standard error ($n = 5$).

duced the largest total AGB (Fig. 2). In sand, RF-amended control plants (Control + RF) had a significantly larger root biomass even though no single nutrient was limiting the system. The RF-amended positive control treatments (Control + RF) were selected as the reference baseline for AGB potential maximum yield at day 62 and day 34 in the soil mixture and sand ($PMY_{62\ days}$ and $PMY_{34\ days}$, dashed lines indicated in Fig. 2).

## 3.1 Phosphorus supply by RF

The accumulated biomass of plants grown with P omitted from the hydroponic, both with (–P + RF) and without RF (–P), was less than 25% and 15% of $PMY_{62\ days}$ for the soil mixture and sand, respectively (Fig. 2). In sand, the –P + RF treatment produced more than twice the amount of AGB than non-amended –P pots at the first harvest (19 days). No differences were observed during the rest of the experiment, where the relative contribution from the first harvest became small due to higher consecutive yields. There was no effect of RF on the accumulated biomass in P-omitted treatments neither on AGB nor on roots. The plant tissue analysis showed that all plants grown without P in the hydroponic were severely deficient of P. No accumulated difference in P uptake was observed (Figs. 3 and 4).

## 3.2 Potassium supply by RF

Plants growing in the K-omitted hydroponic solution showed a positive effect of RF addition on plant growth. RF significantly increased accumulated AGB and root biomass in both the soil mixture and sand when K was otherwise omitted (Fig. 2). In the soil mixture AGB increased by 30%, whereas in sand AGB was four times greater when RF was applied. The –K + RF treatment was not significantly different from $PMY_{34\ days}$, but could not keep up with $PMY_{62\ days}$. Total accumulated K in AGB was significantly higher in RF-amended pots (–K + RF) (Fig. 4). 37 and 26 mg more K $pot^{-1}$ were accumulated in the RF-amended pots compared to where no RF (–K) was added in the soil mixture and sand, respectively. At the first harvest date, shoot K concentration was significantly higher in –K + RF than without RF in both the sand and the soil mixture (Fig. 3); the following harvests did not have increased K concentration, but still produced much more biomass and, thus, took up more K.

## 3.3 Magnesium supply by RF

Plants growing in sand in the –Mg + RF treatment had significantly higher AGB and root biomass than the –Mg treatment (Fig. 2). Accumulated AGB of the –Mg + RF treatment in sand was not significantly different to $PMY_{62\ days}$. This was true albeit the Mg concentration in the tissue was only a fourth of that found in the control plants, and also lower than the deficiency level (Fig. 3). Total accumulated Mg for the –Mg + RF treatment was significantly higher than the Mg content in the –Mg treatment (Fig. 4).

In the soil mixture there was no effect of RF on AGB, root biomass or tissue Mg concentration, and total content in the –Mg + RF compared to –Mg treatments (Figs. 2, 3, and 4).

 

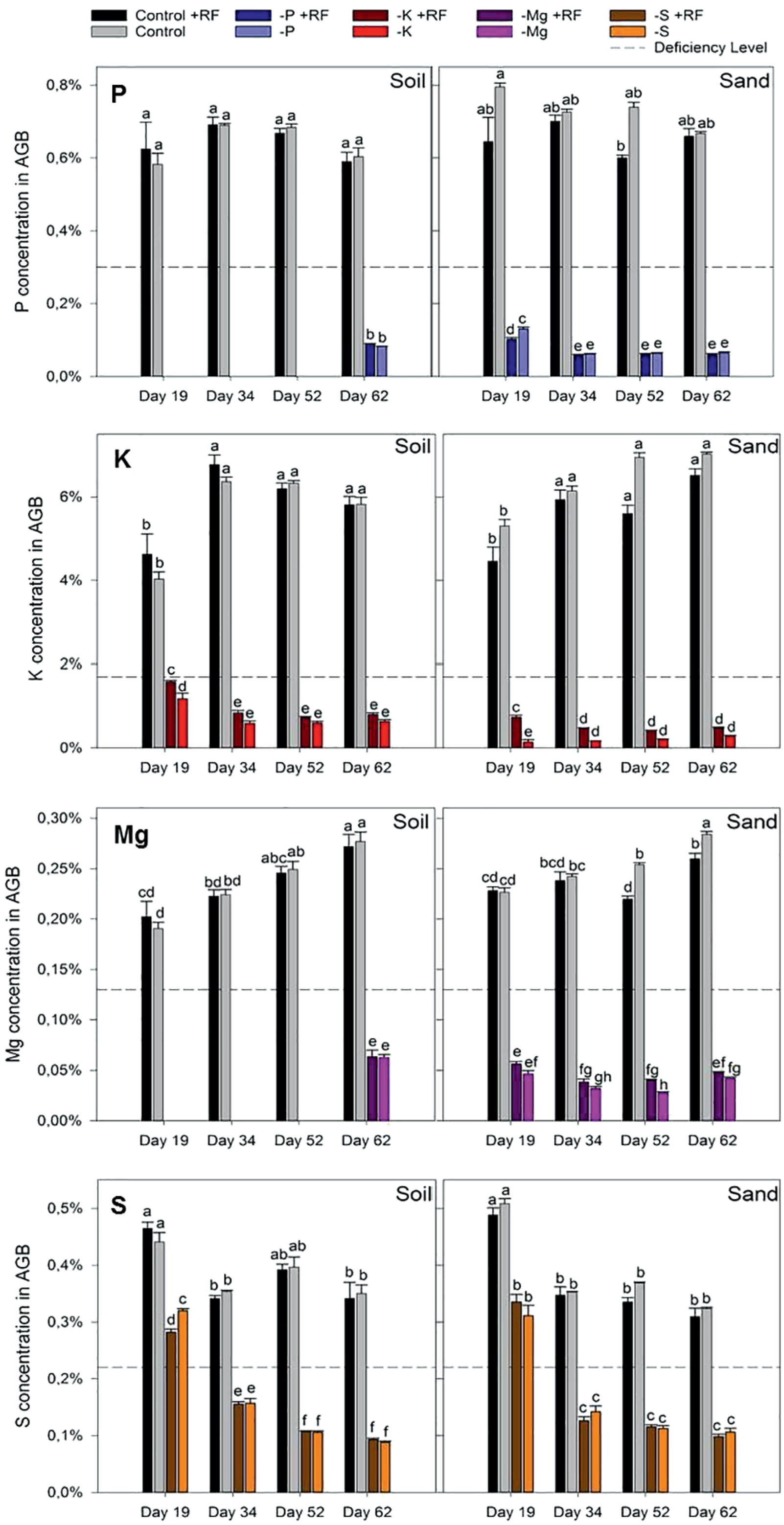


**Figure 3:** Elemental concentration in harvested aboveground biomass (AGB) from ryegrass grown in double-pots after 19, 34, 52, and 62 days. The biomass of the –P and –Mg treatments in the soil mixture was pooled according to weight equivalent to each harvest, and elemental concentrations analysed in the pooled sample, which is depicted here at day 62. Darker colours represent treatments with RF: grey: control, blue: P omitted (–P), red: K omitted (–K), purple: Mg omitted (–Mg) and orange: S omitted (–S). The dotted line shows the deficiency level as indicated by *Pinkerton* et al. (1997). Error bars represent standard error ($n$ = 3).

AGB of –Mg and –Mg + RF in the soil mixture was lower than $PMY_{62\,days}$ (Fig. 2). Ryegrass grown in –Mg treatments in the soil mixture had a higher Mg content than those grown in sand. In the soil mixture the total Mg content in AGB was 8.1 and 7.9 mg with and without RF, respectively, while in sand it was only 5.6 and 2.0 mg.

### 3.4 Sulfur supply by RF

Only at day 19 in the soil mixture the harvested AGB was significantly larger in –S + RF pots than without RF, but for the rest of the harvests RF did not affect accumulated AGB or root biomass (Fig. 2). The accumulated AGB in –S + RF and –S without RF treatments was not significantly different from $PMY_{34\,days}$, but was different from $PMY_{62\,days}$. Sulfur concentration in both –S + RF and –S without RF was sufficient in the first harvest, but became deficient thereafter (Fig. 3). There was no effect of RF on S concentration except at day 19, when the S concentration was lower where RF was added (Fig. 3). The total S content was higher in –S + RF than in –S without RF at day 19 (Fig. 4). Root : shoot biomass was in the range of 0.4–0.5 in the –S + RF and –S treatments in both the soil mixture and sand. This was significantly higher than for the controls (± RF), which had a root : shoot ratio of 0.2 in both the soil mixture and the sand.

## 4 Discussion

Amendment with RF of both the soil mixture and sand enhanced biomass productivity in several treatments. However, the AGB produced did not reach $PMY_{62\,days}$ when RF served as the single source of any nutrient except Mg in sand (Fig. 2). This indicates that nutrient release from RF applied at this rate could not meet crop nutritional demands. Even in cases when RF significantly increased biomass, the tissue concentration of the selected nutrients did not reach above the deficiency levels (Fig. 3). The first hypothesis is rejected as PMY was not reached when P, K or S was omitted from the hydroponic. Nonetheless, there were significant effects on biomass and plant nutrient composition when amending RF. The applied amount of RF was 5% of soil weight, this may seem very high, however, it should be noted, that the soil volume used was also very low compared to the productivity as plants also grew into hydroponics as well.

The difference between the control treatments with and without RF indicated that even when all the essential nutrients were adequately sup-

 

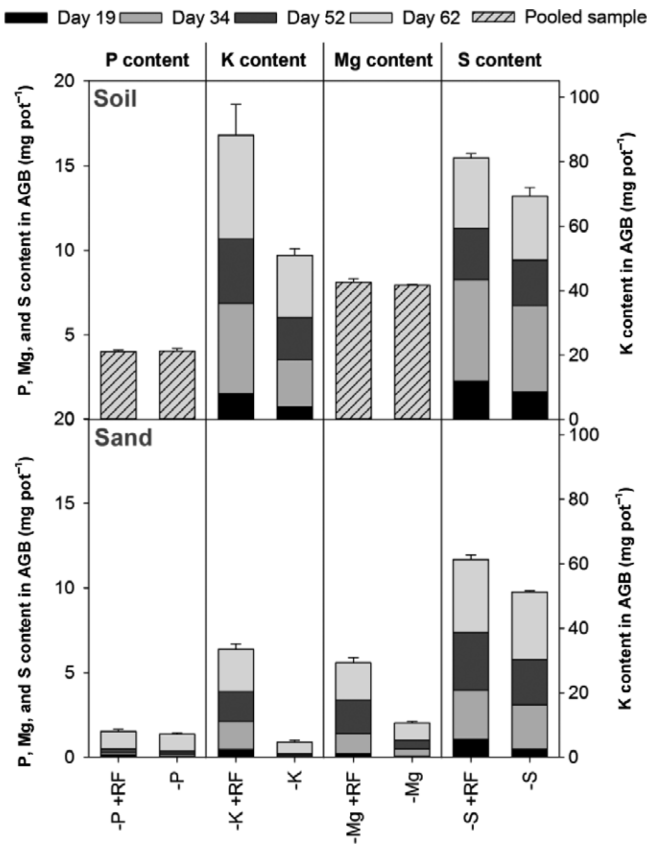


**Figure 4:** Total elemental content (per pot) in harvested aboveground biomass (AGB) for each individual harvest of ryegrass grown in the double-pot systems. Treatment names indicate the omitted nutrient in the hydroponic solution and whether the pots received RF or not. Only the AGB content of the omitted nutrient for each treatment is shown. In soil, AGB P and Mg content in plants grown in P and Mg-omitted hydroponics were analysed as pooled samples, and illustrated here by the diagonally striped bar. Error bars represent standard error (*n* = 3).

plied, the RF may have had some added, non-nutrient-related benefit for plants growing with RF (discussed later). The positive control without RF still produced more biomass than other treatments, which indicates that yield losses below this could reasonably be associated to nutrient deficiency. Caution should be taken when comparing tissue concentrations with the control plants, which grew under conditions with an unlimited supply of all the nutrients. It could be argued that the deficiency line (shown in Fig. 3) is a better reference for comparison purposes since control concentrations may represent excessive or luxury nutrient uptake by plants (*Smith*, 1962; *Chapin III*, 1980).

## 4.1 Phosphorus

Plants grown without P in the hydroponic solution were severely deficient of P. There were no indications that RF could circumvent this deficiency neither through direct supply nor by ion exchange with the soil. RF-initiated ion exchange processes might play a role in other, more P-rich soils, but not in the present soil, which was rather low in P (Tab. 1) and further diluted with sand, which perhaps constrained such interactions, thus the second hypothesis is also rejected.

All the plants, both with and without RF, growing in the P-omitted hydroponic solution had a root : shoot biomass twice that of any other treatment. Enhanced root growth is a common response to P deficiency. The amount of applied RF corresponded to 16.3 mg P pot$^{-1}$. If this entire amount of P had been available to the plants, it should have been sufficient to see a clear response in P uptake and plant growth; however, this was not observed even in sand, where re-sorption could not constrain results. It can be concluded that no orthophosphate was released from RF. If P is released, it is in a form that is not available to plants.

Prevalence of silica ions has been linked to enhanced phosphate availability in soil (*Singh* et al., 2005; *Tubana* et al., 2016; *Kostic* et al., 2017). As the rocks weather, silicic acid is released to the soil. In the literature there is a debate as to whether increased phosphate availability is a direct causality of ion competition for specific sorption sites as suggested by *Brown* and *Mahler* (1989), a causality of pH changes or caused by physiological changes in plants. *Kostic* et al. (2017) have shown Si to affect P acquisition of plants due to upregulation of $P_i$-transporter genes and enhanced organic acid exudation. This is still an area of great debate (*Coskun* et al., 2019), but the results of our study did not support the idea of silicate-promoted enhanced phosphate availability in soil.

## 4.2 Potassium

The application of RF enhanced AGB, root biomass, and tissue K content in both the soil mixture and the sand. K was supplied to an extent where the AGB was not significantly different from $PMY_{34\,days}$ in both the soil mixture and sand, but the accumulated biomass did not reach $PMY_{62\,days}$. A common K-deficiency symptom is low biomass allocation to roots (*Hermans* et al., 2006); this symptom was very pronounced in the ryegrass plants.

The biomass K concentration of the plants growing in hydroponics without K was far below the positive control treatments (Fig. 3). It is possible that K was taken up in excess by the control plants (*Saunders* et al., 1988; *Clover* and *Mallarino*, 2013). *McNaught* (1958) showed how luxury uptake of K can lead to tissue concentrations more than twice that actually required to sustain optimal growth in ryegrass. These findings are similar to the present results where control plants contained 4–6% K, while only 2% should be sufficient for ryegrass according to *Pinkerton* et al. (1997). Still, –K + RF treatments did not reach above the K deficiency level ascertained by *Pinkerton* et al. (1997), nor did the biomass reach $PMY_{62\,days}$ levels, indicating that the K supply from RF at this application rate was still too low to sustain maximum yields alone.

*Bakken* et al. (2000) looked at K supply from seven different crushed rocks on 15 grassland fields in Norway. Some of the tested rocks significantly increased yields and K content in plants compared to where no rocks were applied up to three years after application. The K content in the tested rocks was 2.2–6.6% and all field applications were done at 50 kg K $ha^{-1}$. All, but one of the rock materials, had particle sizes larger than the Greenlandic rock flour applied in our study. The finest of their materials was a feldspar, which did not perform very well compared to the other non-feldspar materials, possibly due to slower dissolution (*Bakken* et al., 2000). *Coroneos* et al. (1995) grew ryegrass (*Lolium rigidum*) and subterranean clover (*Trifolium subterraneum*) with crushed granite powder (< 70 μm) and observed an increased biomass due to enhanced K availability. About 5% of the applied K from granite was solubilised and incorporated into the soil-exchangeable K pool after two months (*Coroneos* et al., 1995). The authors concluded that granite powder has potential as a slow-release K fertilizer. Similarly *Basak* et al. (2018) tested mineral fines of different size fractions from an Australian quarry processing alkaline volcanic rocks. They grew holy basil and maize in sand filled pots mixed 2 : 1 with mineral fines. Also, here they concluded that the rocks had potential as slow release K fertilizer. The findings of our study showed that after 62 days of growth, ryegrass incorporated 4.3–5.8% of the RF–K added to each pot.

In the RF, K-feldspar holds approx. half of the K budget of the material, but it is assumed that this fraction is probably less reactive than the biotite fraction. K-feldspar may have a longer longevity for weathering in soil environments (*White* and *Brantley*, 2003; *Manning* et al., 2017) but are likely not the mineral associated with fast RF K-dissolution such as the case in this experiment. Clay mineral interlayered K is likely not of importance as clay minerals are not found in amounts great enough to be of importance (*Sarkar* et al., 2018). There is an increasing demand for alternative K sources and crushed silicate minerals are a good place to look (*Manning*, 2015; *Basak* et al., 2017). K-bearing minerals include feldspars, micas (*e.g*., muscovite, biotite and phlogopite), zeolite, glauconite, potassium-taranakite, illite, vermiculite, and chlorite (*Basak* et al., 2017). Even though the total K content in the Greenlandic RF is only 2.4%, it still has potential to enter the market as a slow releasing K supplement to maintain healthy K-status of otherwise K depleted soils.

### 4.3 Magnesium

In sand, the –Mg + RF treatments produced more biomass and had a higher Mg uptake than the –Mg treatments without RF. In the soil mixture, no differences were observed. The Mg tissue concentration was higher in plants grown in the soil mixture than in sand. One explanation for this could be that the background Mg content in the soil mixture exceeded the amounts supplied by RF, making the RF-derived Mg pool of less importance in the soil mixture than in the sand. The soil analyses showed that the exchangeable Mg in the soil is intermediate for Danish soils, indicating that the plants may not have been deprived enough for the RF Mg-contribution to make a difference for plant uptake. In sand, less than 1% of the applied RF–Mg was incorporated into AGB. The amount of Mg incorporated into biomass increased over time in sand, indicating slow release and possibly increasing availability of Mg, which could potentially continue for a much longer period than the 62 day duration of our experiment. Excessive luxury uptake of K can also decrease Mg uptake in plants (*Diem* and *Godbold*, 1993; *Gransee* and *Führs*, 2013). In the present case, there was an increased Mg and Ca uptake in the K-deprived treatment, but no pronounced increase in K or Ca uptake compared to the control when Mg was limited (data not shown). Nonetheless, all plants supplied with K may have had an excessive K uptake as discussed earlier. Therefore, it cannot be ruled out that luxury uptake of K in the –Mg treatments occurred as a trade-off with Mg uptake.

### 4.4 Sulfur

Plant AGB and S uptake were not affected by the application of RF. This is not surprising as the S content of RF is only 0.01%, thus, even lower than the P content, where no effect was observed either. The applied S content corresponds to 5 mg S $kg^{-1}$. At the first harvest, plant AGB S concentration was sufficient according to the deficiency levels of *Pinkerton* et al. (1997). Perhaps, due to supply from the seed to sustain growth and thereby also allow AGB to sustain $PMY_{34\,days}$.

An enhanced root : shoot ratio was observed in the –S treatments. Roots in the –S treatment in both the soil mixture and sand were larger than any other treatment. This was quite surprising since S deficiency is not usually known to enhance root growth. However, it may be due to the artificial setup as the excess root growth was mainly in the hydroponic solution itself, rather than in the pot.

### 4.5 Implications and outlook

*Theodoro* and *Leonardos* (2006) evaluated application of native Brazilian quarry rock materials on an agricultural field scale for five years after a single application of 2.5–3 t rock powder $ha^{-1}$ in the first year. After the first crop year, soil chemical analyses showed that the pH, available P, K, and Ca + Mg increased significantly. Even after 5 years all measures were still higher than initially, except for available K, which had declined to levels similar to or below those found before application of rock powders, probably due to improved crop growth during the five years. This indicates that there is a potential for long-term effects of crushed rock amendments. It is likely that RF can be a slow-releasing nutrient source and the full potential of the material therefore needs evaluation on a longer timescale than in the current experiment.

While direct positive nutritional effects were observed for K and partly for Mg in the experiment, there was a general, although non-significant, positive effect of RF application on plant growth and biomass in all the treatments. As mentioned earlier, this could indicate some non-nutrient-related effects. The WHC in the soil, soil mixture and sand was not affected by RF additions at rates up to 10% w : w (data not shown). Even though WHC was not affected in the simple soil testing performed here, this could be a potential long-term benefit of RF in a more natural environment especially in dry climates where evaporation is high and water-scarcity problematic. It is obvious that RF may have a physical impact on soils, particularly on sandy soils with a coarser texture. This is an area of considerable interest in the applied aspects of RF use and an obvious area for future work.

 

For the transport and use of RF from Greenland elsewhere in the world to be commercially viable, the consolidated short and long-term yield effects need to be substantial enough to make RF an attractive alternative to conventional fertilizers. For a material to be marketable and transported worldwide, with nutrient constituents amounting less than 10% of the material's mass, it requires some additional properties of the material to warrant the costs of the product. Soil improving properties could include enhancing water retention, improving aggregation, and liming effects. *Beerling* et al. (2018) have suggested enhanced weathering through amendments of rock powders on agricultural lands as a mechanism for $CO_2$ sequestration. Enhanced weathering is promoted as a negative emissions strategy to meet the 2015 Paris Agreement on climate change (*Edwards* et al., 2017). Such benefits would likely also be true for Greenlandic RF, even though the divalent cation concentration is lower than in basalt and, thus, the $CO_2$ capture potential may be lower than suggested by *Beerling* et al. (2018). Compared to other mineral fertilizers and man-made rock powder products, glacial RF can compete as a more energy-efficient alternative because the material is naturally ground by glaciers and requires no energy input for processing, only for extraction from marine or terrestrial deposits and transportation. Therefore, future work should focus not only on RF as a nutrient source, but also include other aspects of soil improvement for agricultural production, as well as the overall energy use, carbon balance and economic costs of extraction and transport.

## 5 Conclusion

Our findings suggest that there is a potential for using Greenlandic RF as a K and Mg source in agricultural systems where there is lack of these nutrients and where conventional chemical fertilizers are either not available or not desired (*i.e*., certified organic farming). A significant increase in biomass was observed when RF served as the sole source of K in both the sand and the soil mixture. Of the applied K from RF, 5.8% and 4.3% was accumulated in the AGB in soil and sand, respectively. Mg supplied by RF in sand was enough to sustain plant biomass for the entire 62-day period, however, there was no effect of Mg supply from RF when applied to the soil mixture. In sand 0.8% of the applied Mg from RF accumulated in AGB. RF may serve as a slow releasing K and Mg source, but more studies are required to understand the long-term release dynamics. The RF was not capable of supplying P or S. The results did not indicate that soil ion exchange processes were promoted by RF application Inherent soil bound nutrients like P did not become more available with RF application.

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