Nutr Cycl Agroecosyst (2023) 126:51–66
https://doi.org/10.1007/s10705-023-10274-0

ORIGINAL ARTICLE

Greenlandic glacial rock flour improves crop yield in organic agricultural production

Klara Cecilia Gunnarsen · Lars Stoumann Jensen · Minik T. Rosing · Christiana Dietzen

Received: 22 July 2022 / Accepted: 10 March 2023 / Published online: 21 March 2023

Abstract The application of mechanically crushed silicate minerals to agricultural soils has been proposed as a method for both improving crop yields and sequestering inorganic carbon through enhanced mineral weathering. In Greenland, large quantities of finely grained glacial rock flour (GRF) are naturally produced by glacial erosion of bedrock and deposited in easily accessible lacustrine and marine deposits, without the need for energy-intensive grinding. To determine if this material can improve crop yields, we applied 10 and 50 t GRF ha^{-1} to a sandy, organic agricultural field in Denmark. Two field trials were carried out to test the first-year yield response to GRF in both maize and potatoes, residual effects on potato yields in the year after application, and second and third-year residual effects on spring wheat. Reference-K treatments were included for comparison to determine if the beneficial effects of GRF were primarily due to its K content (3.5% K_2O). This alternative source of silicate minerals improved crop yields in the year of application. Though there was no improvement in yield with the reference-K treatments, for each additional ton of GRF applied, maize dry yield increased by 59 kg ha^{-1} and potato tuber yield by an additional 90 kg ha^{-1}. No residual effects on crop yields were observed in the following years, but we suspect that benefits might persist over multiple seasons at sites with lower initial fertility. The increase in yields achieved with GRF could offset some of the costs of applying silicate minerals as a CO_2 sequestration scheme.

Keywords Glacial rock flour · Enhanced rock weathering · ERW · Mineral fertilizer · Potassium · Silicate minerals · Rock dust

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10705-023-10274-0.

K. C. Gunnarsen · L. S. Jensen
Department of Plant and Environmental Sciences, University of Copenhagen, Thorvaldsensvej 40, 1871 Frederiksberg, Denmark

M. T. Rosing · C. Dietzen (✉)
Globe Institute, University of Copenhagen, Øster Voldgade 5-7, 1350 Copenhagen, Denmark
e-mail: christiana.dietzen@sund.ku.dk

Introduction

The application of ground silicate minerals to agricultural soils has been proposed as a mechanism for improving crop yields and soil fertility through the addition of mineral nutrients and soluble silica, in addition to sequestering CO_2 through enhanced mineral weathering (Song et al. 2014; Ramos et al. 2017; Beerling et al. 2018; Haque et al. 2019, 2020a; Amann and Hartmann 2019; Kelland et al. 2020; Jariwala et al. 2022). The weathering of these minerals can be accelerated by incorporation into soils through the action of soil acids as well as root exudates and biologic activity in the rhizosphere (Harley and Gilkes 2000; Violante and Caporale 2015; Gunnarsen et al. 2022). Though the fertilizing effect of the application of local minerals at lower application rates has been extensively studied in Brazil (Manning and Theodoro 2020; Ramos et al. 2021), to date there have only been a limited number of studies examining the degree to which large applications of silicate minerals aimed at sequestering CO_2 through enhanced weathering will improve crop yields (Haque et al. 2019, 2020b; Kelland et al. 2020; Jariwala et al. 2022). Any added crop value would both provide profits for farmers and compensate for some of the total cost of CO_2 uptake. Though the use of crushed mafic or ultramafic rocks, such as basalt or dunite, has frequently been suggested, intensive grinding is needed to achieve a small enough grain size to allow for sufficiently rapid weathering (<100 µm) (Moosdorf et al. 2014). As an alternative, we propose the use of glacial rock flour, a source of silicate minerals available in vast quantities (Bennike et al. 2019; Bendixen et al. 2019) that has been milled by the movement of glaciers over bedrock to ultra-fine grain sizes (D50 <15 µm) and high surface areas that could not be achieved through industrial grinding (Sarkar 2021).

Here we present the results of two field trials aimed at understanding the long-term effects of a large, one-time application of Greenlandic glacial rock flour to a Danish agricultural field in a certified organic arable rotation. As this mineral fertilizer would fall within the requirements for amendments in organic farming, it could therefore be particularly useful in this context as the forms of fertilizing materials permitted for legal use in certified organic farming are limited (Mikkelsen 2007). Previous work on this material has suggested that glacial rock flour can improve growth by serving as a source of available potassium (Gunnarsen et al. 2019), and therefore this experiment was also designed to test if any yield increases could be attributed to the provision of K, in particular.

Materials and methods

Greenlandic glacial rock flour

The rock flour used in this experiment was collected by the Geological Survey of Denmark and Greenland (GEUS) from a marine deposit at the locality Ilulialik (64°45′ 36″ N 50° 39′ 36″ W) in the Nuuk fjord in May, 2016. This material is produced by the glacial erosion of a large area of varied bedrock. The Ilulialik glacial rock flour has a median grain size of 2.6 µm, a BET specific surface area of 19.6 $m^2\ g^{-1}$ (Sarkar 2021), and consists of 27.4% biotite, 18.6% oligoclase/andesine, 14.6% amphibole, 14.1% anorthite, 10.5% quartz, 4.3% Fe-oxide, 2.8% K-feldspar, and 2.4% muscovite (measured with ZEISS Sigma 300VP Field Emission Scanning Electron microscopy by the Geological Survey of Denmark and Greenland). Although the weatherability and total nutrient content of the felsic rocks from which glacial rock flour is derived is lower than that of mafic rocks such as basalt, grain size and density sorting during transport of the material to the fjord has resulted in a rock flour deposit that has a high specific surface area and is enriched in biotite, rendering it more nutrient-dense and highly reactive (Hinsinger et al. 1995; Israeli and Emmanuel 2018). The Ilulialik glacial rock flour has a K_2O concentration of 3.50% (Table 1), 85% of which is likely contained in biotite, which has been shown to be a particularly effective mineral K source for plants due to its rapid weathering rate in soils (Mohammed et al. 2014). The glacial rock flour also contains a variety of beneficial micronutrients, as well as trace amounts of several heavy metals (Table S1). Though these can be toxic to plants at high concentrations, the concentration of elements in the rock flour is comparable to that of the average composition of the continental crust (Rudnick and Gao 2003), and therefore should not be of concern.

Table 1 Glacial rock flour elemental composition and loss on ignition (LOI). (Chemical analysis was performed according to Carignan et al. (2007) by the Centre de Recherches Pétrographiques et Géochimiques (CRPG) at the French National Centre for Scientific Research (CNRS), Nancy, France)

%SiO_2	%Al_2O_3	%Fe_2O_3	%MnO	%MgO	%CaO	%Na_2O	%K_2O	%P_2O_5	%TiO_2	%LOI	%Total
53.99	16.44	8.55	0.12	4.94	3.72	3.84	3.50	0.12	0.71	3.72	99.65

Field site and operations

A field in arable rotation on a certified organic farm was selected near Vojens in Southern Jutland, Denmark (55° 12′ 16.4″ N 9° 15′ 55.9″ E). The loamy sand soils at the site were formed on glacial outwash sands (GEUS, 2020) and are classified as Cambic Arenosols. The mineral component is composed primarily of quartz sand and kaolinite clay with a small amount of feldspar. The mean annual precipitation (2019–2021) for the region according to the Danish Meteorological Institute was 897 mm and the mean annual temperature was 9.4 °C (DMI, Haderslev). As this study was aimed at testing if glacial rock flour would have beneficial effects within the context of organic farming, crop species and baseline fertilization each year was determined by the farmer's plans for the rest of the field. The field trial was managed within the standards of the National Field Trial scheme for Denmark (Landsforsøgene), under the auspices of SEGES (the Danish Knowledge Centre for Agriculture under the Danish Agriculture and Food Council) in collaboration with the local agricultural union and advisory service, Sønderjysk LandboForening.

Two separate trials were conducted at the site- one lasting for three years and the other for two. This allowed us to test not only for the immediate, first-year effects, but also for residual treatment effects in the years following glacial rock flour application. The first trial was initiated on March 1, 2019. The field was prepared with a baseline fertilization of 50 t ha^{-1} of cow manure, corresponding to 170 kg total N ha^{-1} (whereof 100 kg was ammonium-N), 20 kg total P ha^{-1}, and 105 kg total K ha^{-1}. Chemical properties of the soil after baseline fertilization were pH$_{CaCl2}$: 5.1, pH$_{H2O}$: 5.9, Olsen P: 53 mg kg^{-1}, exchangeable K: 69 mg kg^{-1}, and exchangeable Mg: 40 mg kg^{-1} (Dietzen et al. 2022), analyzed according to Danish standards (Sørensen and Bülow-Olsen 1994). Experimental treatments were applied on April 17th, 2019. Treatments included both glacial rock flour and a series of mineral K reference plots aimed at determining the response of yield at this site to added K. For crops with a high K demand, like maize or potatoes, baseline fertilization is usually insufficient on sandy soils with low cation exchange capacity. Therefore, common practice amongst Danish organic farmers is to add at least 80 kg ha^{-1} additional K as either Patentkali® or other approved fertilizing materials like vinasse. Patentkali is a natural mineral evaporite product composed primarily of kieserite ($MgSO_4 \cdot H_2O$) and K_2SO_4 with a small amount of gypsum ($CaSO_4$) and sylvite (KCl) and a nutrient content of 30% K_2O, 10% MgO, and 42.5% SO_3 (K + S Minerals and Agriculture 2022).

In the reference K plots, Patentkali was applied at rates of 0, 161, 321, and 482 kg ha^{-1}, corresponding to 0, 40, 80, and 120 kg K ha^{-1}. Glacial rock flour was applied at two rates, 10 t ha^{-1} and 50 t ha^{-1}, which contain 291 and 1453 kg K ha^{-1}, respectively, though the timeframe over which these nutrients will be released is unknown. Interaction treatments which combined 10 t glacial rock flour ha^{-1} and 50 t glacial rock flour ha^{-1} together with 321 kg Patentkali ha^{-1} were also included to test if, given sufficient K availability, glacial rock flour could further increase crop yield through the provision of other nutrients or effects on soil properties.

The high-rate glacial rock flour treatment was included both to simulate what could be applied over the course of several years and to evaluate residual effects in subsequent cropping years after the one-time application of a high dose. The selected mineral application rates have also served as the basis for several other enhanced weathering studies (Taylor et al. 2015; Kantola et al. 2017; Dietzen et al. 2018; Lefebvre et al. 2019), and therefore allow for comparison with those when estimating CO_2 uptake at the site-the topic of another paper from this project.

The experiment installed in 2019 was arranged as a randomized block design with 4 replicates laid out in a North–South orientation. Plots (3 × 25 m gross plot size) covered 4 rows of plants at a row distance of 750 mm, where the two outer rows and 3.9 m at each end served as a buffer area, resulting in a net plot size of 26 m^2. Prior to planting, the Patentkali reference fertilizer was applied with a plot fertilizer spreader and glacial rock flour was applied manually in 1 m^2 sections to ensure uniform coverage. Seedbed preparation included incorporation of glacial rock flour and Patentkali by harrowing into the top 80 mm of the soil followed by furrowing of the soil. Potatoes were initially seeded in the first year but did not emerge properly due to unforeseen damage of the seed potatoes during storage, so the field was replanted with silage maize instead (Planting and harvest dates in Table S2). The potato ridges were harrowed down and the maize seed bed was prepared with no additional fertilizer application. Maize was sown with the same row placement as the potatoes, but a little later than standard practice. However, according to the farmer's previous experience with maize rotations at the site, the late seeding did not affect the overall maize yield of the field. Maize was harvested after 145 growing days with an experimental silage harvester, leaving a stubble height of 300 mm. Due to problems with the harvester, one block was not harvested properly and therefore these plots are missing from the analysis, leaving three complete replicates for analysis in the first year. The field was left bare with stubble until the following year.

In 2020, the maize stubble was ploughed down before preparing the seedbed, which was planted with potatoes to determine if there were any residual effects of the glacial rock flour in the second growing season after application in 2019. Starch potatoes of the Nofy variety were planted on the entire field at a planting distance of 330 mm and a row distance of 750 mm. Cattle farmyard mature (41 t ha^{-1}) was applied to the entire field as baseline fertilization, corresponding to 166 kg total N ha^{-1} (whereof 98 kg was ammonium-N), 18 kg total P ha^{-1}, and 119 kg total K ha^{-1}. The field was irrigated with a total of 125 mm over the course of the growing season, and potatoes were harvested after 134 growing days with an experimental plot harvester.

A new experiment was also initiated in 2020 aimed at testing the first-year response of potatoes, with plots laid out on both sides of the 2019 experimental area. Three blocks were placed on the west side of the existing experiment and two blocks to the east (Figure S1). Again, a randomized block design was used, and plot size remained the same. However, in the 2020 experiment, 5 replicates were included to increase statistical power. In the newly established blocks, chemical properties of the soil after baseline fertilization with cattle farmyard manure, as described above, were pH$_{CaCl2}$: 5.1, Olsen P: 50 mg kg^{-1}, exchangeable K: 28 mg kg^{-1} and exchangeable Mg: 38 mg kg^{-1}. One row in one of the western blocks was left unplanted in 2020 due to problems with the experimental seeding machinery during potato planting and therefore harvest yields from this year are not available for this block. Another block was excluded from the analysis as it was suspected to have been harvested incorrectly due to abnormally low yields throughout the block, resulting in a total of 3 replicates remaining for analysis in the first growing season. The new plots included the following 5 treatments: a control, reference-K treatments of 241 and 482 kg Patentkali ha^{-1}, corresponding to 60 and 120 kg K ha^{-1}, and the same two glacial rock flour levels as in 2019 (10 and 50 t ha^{-1}). Unlike in 2019, no combined Patentkali and glacial rock flour treatments were included in the 2020 trial design. Application of treatments was carried out in the same manner as in the original plots: glacial rock flour was applied manually in 1 m^2 sections and Patentkali was applied with a plot fertilizer spreader.

Both trials were replanted once more in 2021 with spring wheat, a silica accumulator, to determine if residual effects would differ under a crop that has a greater demand for silica (Ma and Yamaji 2006; Guntzer et al. 2012) and greater ability to weather non-exchangeable K from the soil than potatoes, which may have been less able to access nutrients in the rock flour due to differences in their root systems (Wang et al. 2000; White 2013). The entire field was fertilized with 45 tons of cattle slurry corresponding to 130 kg total N, 19 kg P, and 85 kg K ha^{-1} as baseline fertilization then replanted with spring wheat, allowing for a test of 3rd year residual effects in the 2019 plots and 2nd year residual effects in the 2020 plots. Two weeks after planting of the spring wheat, the field was underseeded with a mix of clover, ryegrass, and festulolium (DSV Frøblanding Nr. 45) and fertilized with 2 kg ha^{-1} of manganese.

Plant analyses

During harvest of aboveground biomass of maize in 2019, the fresh yield weight was determined by automated weighing on the harvester by Haldrup Harvest Manager software, operated by The Danish Technological Institute. Elemental analysis of subsamples of dried and milled plant tissue was subsequently done by Eurofins Denmark (Vejen, Denmark) using aqua regia digestion of samples followed by ICP-OES.

In 2020, aboveground biomass was sampled at midseason (June 26th, 2020) and potato tubers were sampled from all plots at harvest. Aboveground biomass samples were taken three weeks before the onset of fungal induced wilting of the potato plants, at which point the potatoes were still nodulating, the largest potatoes were approximately 20 mm in diameter, aboveground biomass was at a maximum, and very few plants had started to bloom. In the new, first-year experiment (glacial rock flour applied in 2020) two plants from each buffer row were sampled for a total of four plants per plot. In the residual experiment (glacial rock flour applied in 2019), only two plants were cut from each plot. Plants were sampled from the same relative location in all plots to avoid selection bias. Samples were dried at 65 °C for 72 h, achieving a stable weight, then chopped by a cutting mill (Retsch SM 2000). A homogenized subsample was then powderized by thorough mechanical ball milling (shaking with 3 zirconia balls Ø: 15 mm in sample containers for 16 min). These subsamples underwent microwave digestion (UltraWAVE single reaction chamber microwave digestion system, Multiwave 3000, Anton Paar GmbH, Blankenfelde-Mahlow, Germany, software: Milestone Inc, version 1.24) prior to elemental analysis by ICP-OES (Agilent 5100, Agilent Technologies). The second sampling was done at maturity, when potatoes were harvested with an experimental harvester, potato tuber fresh yield was determined for each plot, and 15 washed tubers from each plot were sent for dry matter and starch analysis by a potato starch company (Kartoffelmelscentralen, Denmark). Elemental analysis of harvested potato tissue was done by YARA Analytical Services (Grimsby, UK), also using ICP-OES, according to similar procedures as described previously.

In 2021, spring wheat was harvested from both experiments with an experimental harvester. Grain dry matter yield was determined for each plot and yield values corrected to a uniform 15% moisture content. Elemental analysis of plant material was not performed in 2021.

Statistical analysis

Treatment effects on yield, concentrations of K, Mg, P, and Ca in plant biomass, and total plant uptake of these elements for each of the two trials were analyzed using linear mixed effects models ('lmerTest') in R version 4.1.2 ($\alpha = 0.05$) (Kuznetsova et al. 2017). Models for yield with and without quadratic components were compared to determine if a non-linear growth curve better fit the data, but inclusion of a quadratic term did not significantly improve any of the models and thus quadratic components were not included in our analysis. Residual plots of all models were inspected to ensure the assumptions of normality and homogeneity of residuals were met. Yield metrics used were total dry maize biomass (kg ha^{-1}) in 2019, tuber fresh weight (kg ha^{-1}) in 2020, and wheat grain yield at 15% moisture (kg ha^{-1}) in 2021.

The effects of Patentkali in the reference K plots were analyzed separately from the glacial rock flour plots in the 2019 experiment. The rate of Patentkali applied was included in the model as a numeric predictor with growing season (1st, 2nd, or 3rd growing seasons after treatment) as an interacting categorical variable (Piepho and Edmondson 2018). The random effects term included plot nested within block to account for the experimental design and repeated measures over time, with separate variances for each growing season to account for heteroskedasticity. The same model was also used to analyze the effects of Patentkali on plant nutrient concentrations and uptake.

The effect of glacial rock flour in the 2019 plots, both alone and in combination with Patentkali, was modelled with glacial rock flour treatment rate as a numerical predictor interacting with both growing season and Patentkali, both of which were included as categorical fixed effects. The random effects term also included plot nested within block and separate variances for each growing season. Two data points for yield and total element uptake were missing from the second-year data from the original plots (one from a 10 t glacial rock flour ha^{-1} plot, and one from a 10 t glacial rock flour ha^{-1} + Patentkali plot). Potato starch content was missing from one 50 t glacial rock flour ha^{-1} plot, thus starch yields were missing from 3 plots all together.

The results of the experiment established in 2020 were also analyzed with a linear mixed effects model with the same random effects as previously described, but with both glacial rock flour and Patentkali application rate included as numeric predictors that each interacted with growing season, a categorical variable, but not with one another.

Within each growing season, the significance of the slope coefficient for the treatment effect on each response variable was tested using 'emtrends' in the 'emmeans' package, using the Satterthwaite method for degrees of freedom (Lenth 2022).

Response variables that were only measured in one season (Table S3), including potato quality indicators (dry matter content, tuber dry yield, starch content, and starch yield) and aboveground biomass K concentration, calcium concentration and uptake in the 2019 experiment, and tuber elemental concentrations and uptake in the 2020 experiment, were analyzed in a model that did not include growing season in the main effects or plot in the random effects.

Results

2019 experiment

In the 2019 reference K plots, increasing levels of Patentkali had no significant effect on yield, though total maize K uptake did significantly increase with treatment in the year of application ($p=0.042$) (Fig. 1, Table 2). This increase in uptake did not persist in the following season, but potato tuber K concentration was elevated in the treated plots ($p=0.034$), as was aboveground biomass K concentration ($p=0.020$). The application of Patentkali had no effect on plant Mg and P concentration or uptake but did result in a significant decrease in maize Ca concentration with treatment ($p=0.041$), though total Ca uptake was not significantly impacted. There was no residual effect of Patentkali on the dry matter content and yield of potatoes or the starch content and yield.

In the year of application, yield significantly increased with the application of glacial rock flour alone ($p=0.018$) at a rate of 59 kg ha^{-1} of maize dry matter per ton of glacial rock flour applied (Fig. 1). However, when glacial rock flour was applied to plots that had also received Patentkali, there was no increase with treatment. In the following years, there was no significant residual effect of glacial rock flour on the yield of potatoes or spring wheat. Likewise, glacial rock flour significantly increased total plant K uptake ($p<0.001$) in the year of application when not combined with Patentkali, but had no significant effect in the combined plots and no residual effect with or without Patentkali in the following year and did not result in increased K concentration in the potato aboveground biomass.

Glacial rock flour did not significantly affect plant P, Mg, or Ca concentrations and did not significantly affect Ca, with or without Patentkali. However, when not combined with Patentkali, total P uptake did increase with glacial rock flour in the first year ($p=0.029$), and total Mg uptake increased in the first year ($p=0.014$) but decreased in the second year ($p<0.001$).

Glacial rock flour significantly decreased the tuber dry yield ($p=0.021$) in the second growing season when not combined with Patentkali. Tuber dry matter content was also reduced with glacial rock flour, both with ($p=0.049$) and without Patentkali ($p=0.020$). Glacial rock flour had no residual effect on potato starch content, total starch produced, or aboveground biomass K concentration.

2020 experiment

In the reference K plots installed in 2020, there was no significant increase in yield with the addition of Patentkali in either the 1st or 2nd growing season (Table 2, Fig. 2). Patentkali also had no significant effect on tuber dry matter content and yield, starch content and yield, or K concentration, but did increase total tuber K uptake ($p=0.040$), as well as potato mid-season aboveground biomass K concentration ($p=0.014$). There was no difference in tuber concentration or uptake of Mg or P, or aboveground biomass Ca, Mg, or P concentration.

The application of glacial rock flour was observed to significantly increase fresh potato tuber yields by 95 kg ha^{-1} per ton of glacial rock flour ($p=0.003$) but had no residual effect on spring wheat in the following year. Tuber K concentration ($p=0.039$) and uptake ($p=0.016$) both increased significantly with glacial rock flour, but there was no effect on tuber dry matter content and yield or starch content and yield. The K concentration ($p=0.003$) of the aboveground potato plants sampled at mid-season also increased with glacial rock flour. However, there was no significant effect of glacial rock flour on tuber P or Mg concentration, tuber P and Mg uptake, or aboveground biomass P, Mg, or Ca concentration.

Discussion

Glacial rock flour increases yield

The observed increases in crop yield in the year of application confirms the fertilizing potential of glacial rock flour. However, the addition of Patentkali

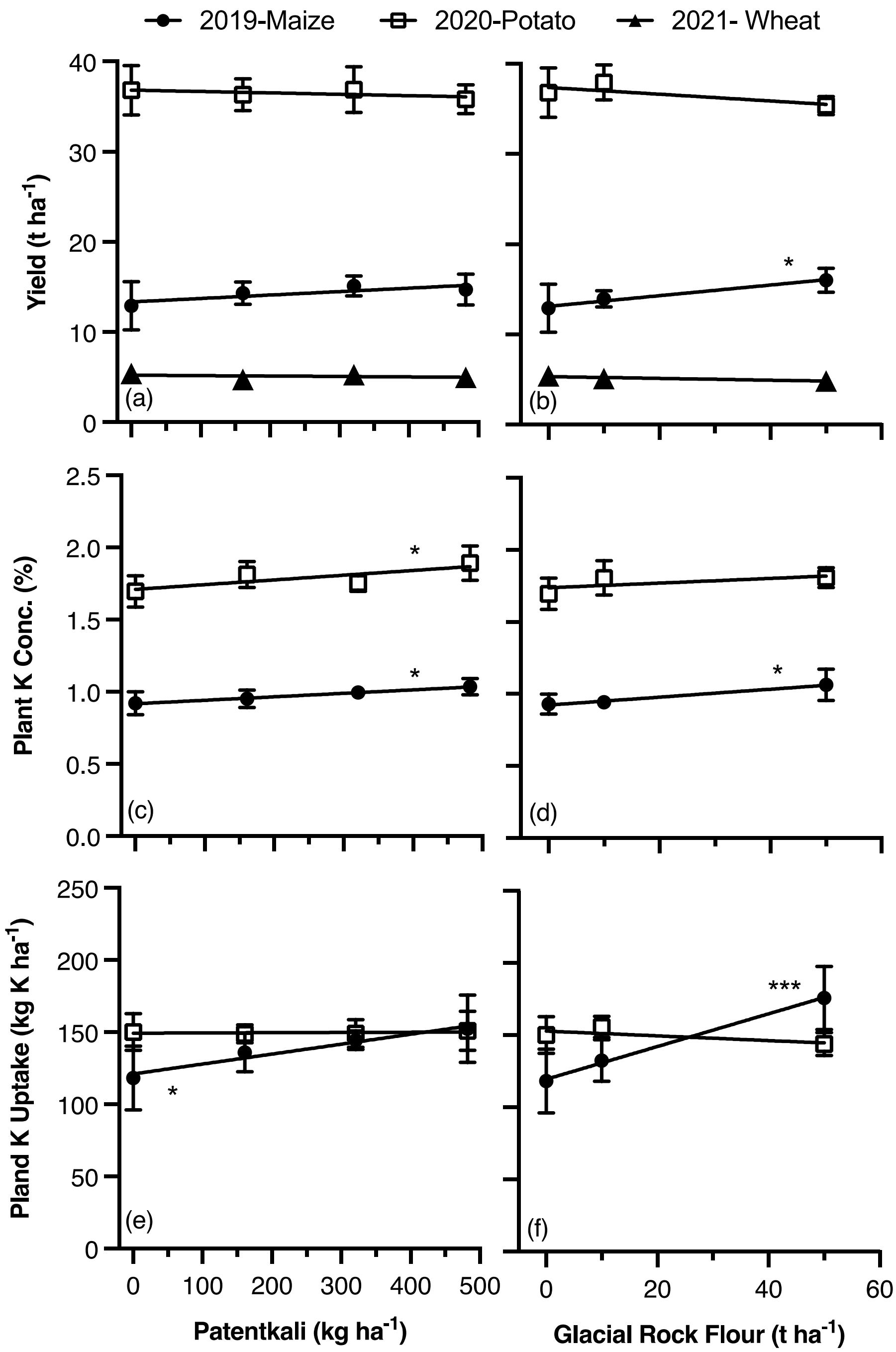

Fig. 1 Crop yield (total maize dry matter, 2019; potato tuber fresh matter, 2020; grain at standard 15% moisture, 2021), plant K concentration, and total plant K uptake in the experiment installed in 2019 for each measured growing season as a function of Patentkali and glacial rock flour application rate. Error bars are SD. Asterisks indicate significance: *$p<.05$; **$p<.01$; ***$p<.001$

and glacial rock flour concurrently in the 2019 plots resulted in no increases in yield. As this difference in response appears to be due to overfertilization with K in the combined treatments, causing soil exchangeable cation imbalances (See Supplementary Material for further discussion of combined treatments), we do not consider these treatments further, as they did not accomplish what they were designed to do- give insight into the possibility of additional nutritional or physical benefits of glacial rock flour amendments when K is not limiting. We also did not repeat the combined treatment when the second experiment was installed in 2020 for similar reasoning.

Table 2 Model coefficients (slope and intercept) for measured response variables as affected by each treatment at each time point measured for both the 2019 experiment and the 2020 experiment, where 1st season represents the year of application

	2019 experiment					2020 experiment				
	Season	Treatment	Intercept	Slope	*p*- value	Season	Treatment	Intercept	Slope	*p*-value
Yield (kg ha^{-1})	1st	*GRF*	13,123.77	59.12	0.018*	1st	*GRF*	33,845.052	94.600	0.003**
		GRF + Patentkali	14,604.74	− 6.69	0.766					
		Patentkali	13,345.036	3.822	0.186		*Patentkali*	33,845.052	5.242	0.062
	2nd	*GRF*	37,487.24	− 38.84	0.176	2nd	*GRF*	4793.456	4.170	0.433
		GRF + Patentkali	10,129.52	0.90	0.974					
		Patentkali	36,832.151	− 1.542	0.496		*Patentkali*	4793.456	− 0.079	0.882
	3rd	*GRF*	5333.99	− 9.93	0.077					
		GRF + Patentkali	11,524.25	1.57	0.770					
		Patentkali	5224.358	− 0.475	0.474					
% K	1st	*GRF*	0.92	2.75E−03	0.064	1st	*GRF*	1.707	3.42E−03	0.039*
		GRF + Patentkali	1.03	1.64E−03	0.252					
		Patentkali	0.909	1.89E−04	0.220		*Patentkali*	1.707	3.15E−04	0.055
	2nd	*GRF*	1.74	1.62E−03	0.287					
		GRF + Patentkali	0.89	3.05E−03	0.055					
		Patentkali	1.709	3.27E−04	0.034*					
K uptake(kg ha^{-1})	1st	*GRF*	11.95	1.13E−01	< .001***	1st	*GRF*	137.6	4.93E−01	0.016*
		GRF + Patentkali	14.28	2.41E−02	0.321					
		Patentkali	120.32	6.46E−02	0.042*		*Patentkali*	137.6	4.03E−02	0.040*
	2nd	*GRF*	15.39	− 1.80E−02	0.131					
		GRF + Patentkali	9.21	1.83E−03	0.873					
		Patentkali	149.30	1.75E−03	0.849					
% P	1st	*GRF*	0.175	− 1.43E−04	0.370	1st	*GRF*	0.213	5.65E−05	0.880
		GRF + Patentkali	0.159	1.79E−04	0.265					
		Patentkali	0.170	− 2.90E−05	0.300		*Patentkali*	0.213	1.99E−05	0.598
	2nd	*GRF*	0.206	1.79E−04	0.607					
		GRF + Patentkali	0.201	2.86E−04	0.414					
		Patentkali	0.207	2.34E−05	0.275					

Table 2 (continued)

	2019 experiment					2020 experiment				
	Season	Treatment	Intercept	Slope	*p*- value	Season	Treatment	Intercept	Slope	*p*-value
P uptake (kg ha^{-1})	1st	*GRF*	2.256	9.46E−03	0.029*	1st	*GRF*	17.16	2.83E−02	0.209
		GRF + *Patentkali*	2.246	2.03E−03	0.605					
		Patentkali	22.65	2.23E−03	0.672		*Patentkali*	17.16	3.36E−03	0.144
	2nd	*GRF*	1.829	− 2.42E−03	0.261					
		GRF + *Patentkali*	2.267	− 9.87E−04	0.641					
		Patentkali	18.11	− 1.13E−03	0.340					
% Mg	1st	*GRF*	0.111	− 1.12E−04	0.302	1st	*GRF*	0.103	− 1.24E−04	0.400
		GRF + *Patentkali*	0.100	4.29E−05	0.691					
		Patentkali	0.109	− 2.20E−05	0.187		*Patentkali*	0.103	− 2.34E−06	0.872
	2nd	*GRF*	0.103	− 7.14E−05	0.542					
		GRF + *Patentkali*	0.125	1.61E−04	0.178					
		Patentkali	0.102	1.56E−05	0.330					
Mg uptake (kg ha^{-1})	1st	*GRF*	1.444	6.50E−03	0.014*	1st	*GRF*	8.33	− 2.35E−04	0.985
		GRF + *Patentkali*	1.434	− 8.32E−05	0.971					
		Patentkali	14.440	9.78E−04	0.770		*Patentkali*	8.33	6.28E−04	0.612
	2nd	*GRF*	0.944	− 2.85E−03	< .001***					
		GRF + *Patentkali*	1.393	9.66E−05	0.888					
		Patentkali	8.947	− 2.05E−04	0.830					
% Ca	1st	*GRF*	0.121	− 2.37E−04	0.173					
		GRF + *Patentkali*	0.111	− 1.95E−04	0.261					
		Patentkali	0.127	− 5.11E−05	0.041*					
Ca uptake (kg ha^{-1})	1st	*GRF*	1.623	3.66E−03	0.079					
		GRF + *Patentkali*	1.610	− 3.89E−03	0.064					
		Patentkali	16.64	− 2.04E−03	0.463					

P-value indicates significance of the slope compared to a null model

Asterisks indicate significance: *$p < .05$; **$p < .01$; ***$p < .001$

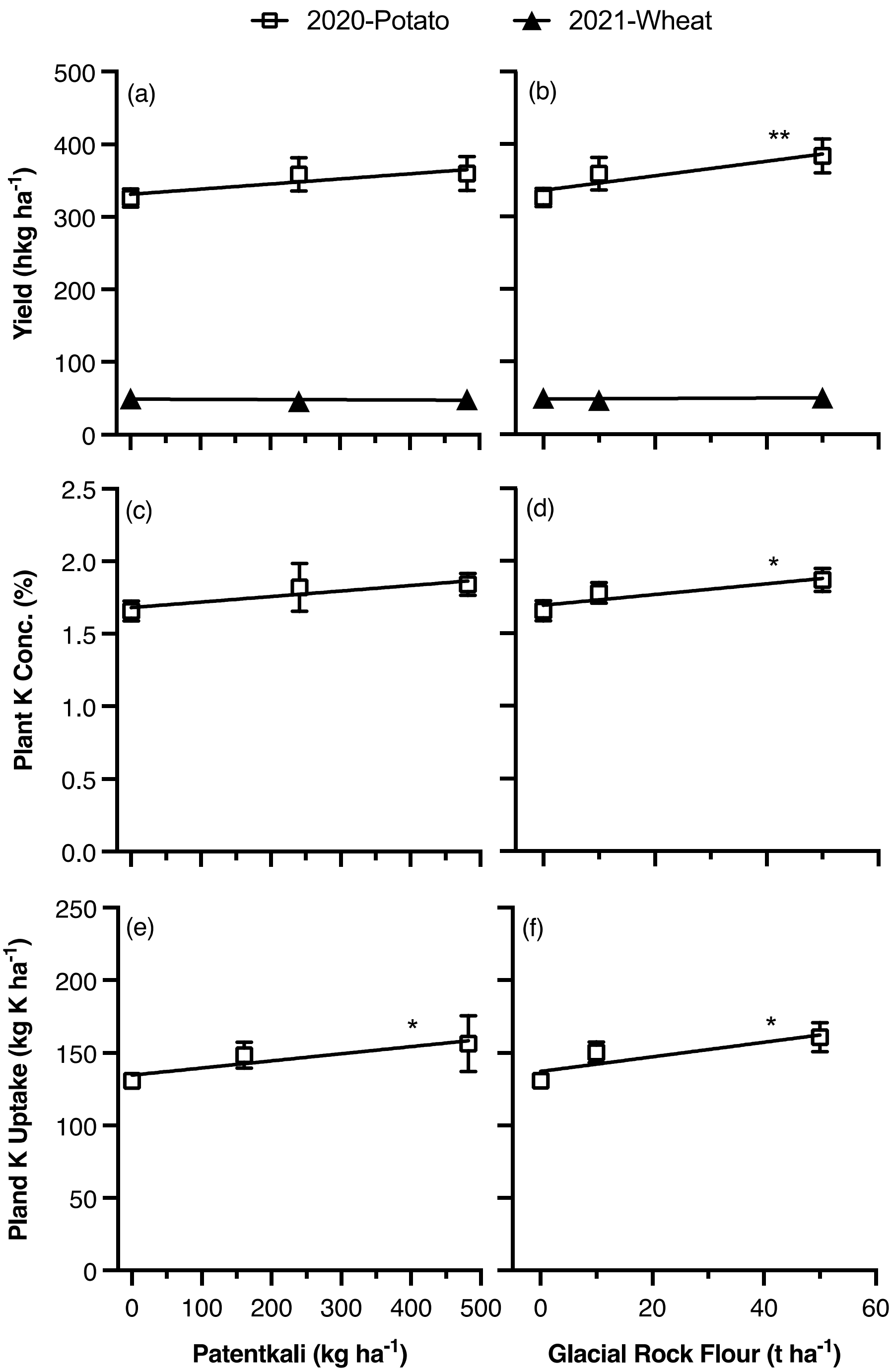

Fig. 2 Crop yield (potato tuber fresh matter, 2020; grain at standard 15% moisture, 2021), plant K concentration, and total plant K uptake in the experiment installed in 2020 for each measured growing season as a function of Patentkali and glacial rock flour application rate. Error bars are SD. Asterisks indicate significance: $^{*}p<.05$; $^{**}p<.01$; $^{***}p<.001$

Though the combined treatments did not prove to be useful in determining any additional benefits of glacial rock flour in the presence of sufficiently supplied K, it is worth noting that the highest yields in the year of treatment application were obtained with 50 t ha^{-1} of glacial rock flour in both 2019 and 2020. Unlike Patentkali, which increased plant K uptake but not yield, glacial rock flour was able to significantly increase yield, indicating that it was more effective than standard fertilization practices at the site.

Additional benefits of glacial rock flour

Given the observed increases in yield, K concentration, and uptake of K with the application of glacial rock flour, it is likely that the K input from glacial rock flour did contribute to the increased yields with treatment at this site (Jarrell and Beverly 1981). It appears that any K released by the weathering of the rock flour was taken up by the crops, as no differences in soil K availability with treatment were observed (Dietzen et al. 2022; Dietzen and Rosing 2023). However, the fact that K fertilization alone did not achieve similar effects indicates the importance of ensuring appropriate availability ratios of essential nutrients to avoid imbalances which can hinder growth (Bedi and Sekhon 1977). It is therefore presumably the combination of K with other plant macro- and, perhaps, micro-nutrients contained in glacial rock flour that results in increased yield. For example, total maize uptake of both P and Mg significantly increased with glacial rock flour in the year of application, and total potato Ca uptake also increased with glacial rock flour in the first year. These changes could be the cause of the higher maize yield with glacial rock flour but absence of effect of reference K addition (Fig. 1), although soil physical effect or effects on the soil microbiome cannot be ruled out (Gunnarsen et al. 2022).

The plants may have also benefitted from Si released upon rock weathering (Gocke et al. 2013; Cornelis and Delvaux 2016; Gunnarsen et al. 2022). This is a field of growing interest, as Si can improve both plant nutrient uptake and nutrient use efficiency (Neu et al. 2017; Aqaei et al. 2020) as well as resistance to abiotic and biotic stressors, although the mechanisms are not yet fully understood (Tubana et al. 2016; Puppe and Sommer 2018). These effects are often seen on strongly weathered soils but may also have importance for crop performance on temperate soils (Clymans et al. 2011), especially sandy soils.

It is also possible that surface properties of glacial rock flour could buffer soil acidification or contribute to enhanced cation exchange capacity and thus improved aggregation (Bedel et al. 2018). Furthermore, with high application doses or repeated application, the particle size distribution will shift to a higher proportion of fine grains. This can have impacts on soil water holding capacity, especially on sandy soils where it may lead to an increased reserve of plant available moisture (de Oliveira Garcia et al. 2020).

Initial site properties impact response

Despite the many potential beneficial impacts of glacial rock flour applications, as with any fertilizer, crop nutrient requirements and initial site properties must be taken into account before determining how much of this material to apply. Though there is a significant increase in potato tuber yield in the year of application with glacial rock flour, its effects on potato quality parameters tended to be negative (Table 3). In the year of application, no increase in potato dry matter content was observed, whereas in the year after application, potato dry matter content and dry yield actually decreased with glacial rock flour application. This is not entirely surprising, as excessive K fertilization (above the relatively high K demand of potatoes) has been shown to have contradictory effects on potato quality (Laboski and Kelling 2007; Torabian et al. 2021). Though potato dry matter content sometimes increases with K application, particularly in K deficient soils, excess K often results in decreased quality due to increased translocation of the nutrient to tubers which results in increased tuber water absorption and lower dry matter content (Panique et al. 1997; Stark et al. 2004), which was observed in the residual glacial rock flour treatment plots. According to Stark et al. (2004), the optimum tuber K concentration for maximum production of dry matter is 1.8%. The addition of any treatment, either Patentkali or glacial rock flour (with the exception of 321 kg ha^{-1} Patenkali alone in 2019 plots), raised the mean tuber K concentration above this threshold, further suggesting that K has been supplied at rates in excess of that needed to achieve maximum potato yield (Panique et al. 1997).

Given the rather high level of baseline fertilization at this farmer's field site, which contributed to adequate soil nutrient availability in advance of the experiment, the lack of effect after the first year is not entirely surprising. In 2021, average yields for spring wheat (at 85% dry matter content) in the Southern Denmark region were 4.7 t ha^{-1} (Statistics Denmark 2021), which is lower than all observed treatment means at the trial site, including the control (Figs. 1, 2). This suggests that yield increases due to residual

Table 3 Model coefficients (slope and intercept) for measured potato quality parameters and aboveground biomass K concentration as affected by each treatment for both the 2019 experiment and the 2020 experiment, where 1st season represents the year of application, 2nd the subsequent year of residual value. *P*-value indicates significance of the slope compared to a null model

2019 Experiment						2020 Experiment				
	Season	Treatment	Intercept	Slope	p−value	Season	Treatment	Intercept	Slope	p−value
% Dry matter	2nd	*GRF*	23.78	−2.66E−02	0.049	1st	*GRF*	23.87	23.87–2.76E−02	0.196
		GRF+Patentkali	22.98	−3.21E−02	0.020*					
		Patentkali	23.77	−3.07E−03	0.054		*Patentkali*	23.87	−1.40E−03	0.501
Potato dry yield (kg ha^{-1})	2nd	*GRF*	8974.38	−1.95E+01	0.021*	1st	*GRF*	8077.7	11.16E+01	0.228
		GRF+Patentkali	8277.63	−1.14E+01	0.150					
		Patentkali	8762.54	−1.50E+00	0.105		*Patentkali*	8077.71	7.56E−01	0.428
% Starch	2nd	*GRF*	18.96	6.39E−03	0.492	1st	*GRF*	18.94	−1.17E−02	0.345
		GRF+Patentkali	18.61	6.84E−05	0.994					
		Patentkali	19.12	−9.04E−04	0.224		*Patentkali*	18.94	−1.57E−03	0.216
Starch yield (kg ha^{-1})	2nd	*GRF*	7110.22	−2.40E+00	0.740	1st	*GRF*	5354.10	6.61E+00	0.463
		GRF+Patentkali	6711.27	−1.63E−01	0.980					
		Patentkali	7034.24	−5.92E−01	0.275		*Patentkali*	5354.10	1.19E−01	0.895
Aboveground biomass %K	2nd	*GRF*	6.61	1.34E−02	0.254	1st	*GRF*	6.46	2.83E−02	0.003**
		GRF+Patentkali	7.31	−1.49E−02	0.207					
		Patentkali	6.24	1.89E−03	0.020*		*Patentkali*	6.46	8.82E−03	0.014*

Asterisks indicate significance: *$p<.05$; **$p<.01$; ***$p<.001$

treatment effects may not have been observed because yields had already approached their potential maximum. Even though we did not observe any significant effects of residual treatments on yield in the 2nd or 3rd year crops, it is possible that glacial rock flour may have a more long-term effect if soils at the site were more nutrient poor, as has been observed with other forms of fertilizer as well. Tropical soils, for example, which generally have lower soil fertility, are often more responsive to soil amendments compared to temperate soils in arable rotation (Van Straaten 2002; Jeffery et al. 2017).

Comparison with other silicate mineral amendments

The high level of baseline fertilization at this site combined with the variation in grain sizes and application rates of other silicate minerals that have been applied with the goal of CO_2 sequestration makes direct comparison of increases in yield difficult, though both basalt and wollastonite have also been found to have beneficial effects on yield (Haque et al. 2019, 2020b; Kelland et al. 2020; Jariwala et al. 2022). In the year of application, 50 t ha^{-1} of glacial rock flour increased maize yields by 24% and potato tuber yields by 19%. In comparison, Kelland et al. (2020) observed a 21% increase in sorghum yield when 100 t ha^{-1} of ground basalt was applied in a mesocosm study to a UK clay loam soil. Though the particle size of the basalt they used was many times greater (50–150 μm), the fact that their application rate was twice as high as ours resulted in a total surface area of the applied material approximately 60% greater than that of glacial rock flour at 50 t ha^{-1}, yet a comparable increase in yield. In another mesocosm study, Vienne et al. (2022) applied 50 t ha^{-1} of basalt (BET surface area: 9.23 m^2 g^{-1}) to potatoes. The larger grain size of this basalt only provided approximately half of the weatherable surface area of glacial rock flour at the same application rate, and no significant increase in potato tuber yield was observed, though there was a non-significant trend towards a much smaller increase (5.5%) (Vienne et al. 2022). However, our observed yield increases were significantly less than the 90% increase in maize dry biomass found by Haque et al., (2019) in a pot study with wollastonite. The grain size and surface area of this material (D90: 25.9 μm; BET surface area: 20.28 m^2 g^{-1}) were comparable to that of glacial rock flour, but the application rates were higher still-wollastonite powder comprised 11.1% of the growing medium, and the remainder was agricultural soil from a bean field near Guelph, Ontario. Assuming a 250 mm mixing depth, at our site 50 t ha^{-1} equates to a glacial rock flour addition of just 2%, implying that their treatment provided 5.74 times as much reactive surface area—likely an impractical amount unless the field is very near the source of the applied minerals. In another study of microplots planted with alfalfa amended with less fine grained wollastonite (D90: 63.7 μm; BET surface area: 3.467 m^2 g^{-1}) at lower application rates of 30 t ha^{-1} and 100 t ha^{-1}, increases in aboveground biomass of 28% and 100%, respectively, were observed (Haque et al. 2020b). Experimental comparison under uniform conditions is needed to better compare agricultural impacts of the various sources of silicate minerals that have been proposed for use in CO_2 sequestration via enhanced weathering.

Conclusion

These experiments showed for the first time that the application of glacial rock flour has the potential to increase crop yields and serve as a source of K if applied at the high rates of silicate mineral application proposed for CO_2 uptake via enhanced weathering by Taylor et al. (2015). As the number of fertilizing materials approved for organic agriculture are limited, the fact that glacial rock flour showed a significant effect in this context is particularly promising. Even though we did not detect any residual effects of the glacial rock flour in the years after application in these trials, the fact that glacial rock flour increased yields when a reference K fertilizer did not suggests that glacial rock flour provides additional benefits over and above that just of K supply. Given the already relatively sufficient supply of K at this site and lack of response to standard fertilization practices, the ability of glacial rock flour to increase yields in the year of application confirms its potential to increase agricultural productivity, which may compensate for some of the offset costs of CO_2 uptake via enhanced rock weathering. However, a full life cycle assessment should be conducted before application at a particular location to determine the sustainability of the practice when transportation from Greenland is accounted for. Further research should be conducted to determine if residual effects occur when glacial rock flour is applied to more nutrient poor soils, which may have a stronger response in the long-term.

Acknowledgements This work was funded by the Novo Nordic Foundation (grant number: NNF16SH20278). We would like to thank the farmer Flemming Skov and the personnel at SEGES (National agricultural knowledge and innovation center) and SLF (Sønderjysk Landboforening) and specifically Lea Staal and Anette Dam who monitored the field and helped answer questions related to field status and how the plants were growing.

Author contributions Conceptualization, MTR and LSJ; methodology, LSJ, KCG, and CD; formal analysis, CD; investigation, KCG; writing—original Draft, CD and KCG; writing—review & editing, CD, KCG, LSJ, and MTR; visualization: CD; funding acquisition, MTR; supervision, LSJ and MTR.

Data availability The datasets generated during and analyzed during the current study are available in the University of Copenhagen's Electronic Research Data Archive at the following address: https://doi.org/10.17894/UCPH.16FBF798-6DE6-40D6-8437-E70CD0A42FC1. Additional information can be found in the Supplementary Material.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

References

Amann T, Hartmann J (2019) Ideas and perspectives : synergies from co-deployment of negative emission technologies. Biogeosciences 16:2949–2960. https://doi.org/10.5194/bg-16-2949-2019

Aqaei P, Weisany W, Diyanat M et al (2020) Response of maize (*Zea mays* L.) to potassium nano-silica application under drought stress. J Plant Nutr 43:1205–1216. https://doi.org/10.1080/01904167.2020.1727508

Bedel L, Legout A, Poszwa A et al (2018) Soil aggregation may be a relevant indicator of nutrient cation availability. Ann for Sci 75:1–12. https://doi.org/10.1007/s13595-018-0782-y

Bedi AS, Sekhon GS (1977) Effect of potassium and magnesium application to soils on the dry-matter yield and cation composition of maize. J Agric Sci 88:753–758. https://doi.org/10.1017/S0021859600037485

Beerling DJ, Leake JR, Long SP et al (2018) Farming with crops and rocks to address global climate, food and soil security. Nat Plants. https://doi.org/10.1038/s41477-018-0108-y

Bendixen M, Overeem I, Rosing MT et al (2019) Promises and perils of sand exploitation in Greenland. Nature Sustainability 2:98–104. https://doi.org/10.1038/s41893-018-0218-6

Bennike O, Jensen JB, Sukstorf FN, Rosing MT (2019) Mapping glacial rock flour deposits in Tasersuaq, Southern West Greenland. Geol Surv Den Greenl Bull 43:1–5. https://doi.org/10.34194/GEUSB-201943-02-06

Clymans W, Struyf E, Govers G et al (2011) Anthropogenic impact on amorphous silica pools in temperate soils. Biogeosciences 8:2281–2293. https://doi.org/10.5194/bg-8-2281-2011

Cornelis JT, Delvaux B (2016) Soil processes drive the biological silicon feedback loop. Funct Ecol 30:1298–1310. https://doi.org/10.1111/1365-2435.12704

de Oliveira GW, Amann T, Hartmann J et al (2020) Impacts of enhanced weathering on biomass production for negative emission technologies and soil hydrology. Biogeosciences 17:2107–2133. https://doi.org/10.5194/bg-17-2107-2020

Dietzen C, Rosing M (2023) Quantification of CO_2 uptake by enhanced weathering of silicate minerals applied to acidic soils. Int J Greenh Gas Control 125. https://doi.org/10.1016/j.ijggc.2023.103872

Dietzen C, Harrison R, Michelsen-Correa S (2018) Effectiveness of enhanced mineral weathering as a carbon sequestration tool and alternative to agricultural lime: an incubation experiment. Int J Greenh Gas Control 74:251–258. https://doi.org/10.1016/j.ijggc.2018.05.007

Dietzen C, Gunnarsen KC, Jensen LS, Rosing MT (2022) Glacial rock flour field trial. University of Copenhagen, Vojens, Denmark

Gocke M, Liang W, Sommer M, Kuzyakov Y (2013) Silicon uptake by wheat: effects of Si pools and pH. J Plant Nutr Soil Sci 176:551–560. https://doi.org/10.1002/jpln.201200098

Gunnarsen KC, Schjoerring JK, Gómez-Muñoz B et al (2022) Can silicon in glacial rock flour enhance phosphorus availability in acidic tropical soil? Plant Soil. https://doi.org/10.1007/s11104-022-05399-0

Guntzer F, Keller C, Meunier JD (2012) Benefits of plant silicon for crops: a review. Agron Sustain Dev 32:201–213. https://doi.org/10.1007/s13593-011-0039-8

Haque F, Santos RM, Dutta A et al (2019) Co-Benefits of wollastonite weathering in agriculture: CO2 sequestration and promoted plant growth. ACS Omega 4:1425–1433. https://doi.org/10.1021/acsomega.8b02477

Haque F, Santos RM, Chiang YW (2020) CO_2 sequestration by wollastonite-amended agricultural soils – an Ontario field study. Int J Greenh Gas Control 97:103017. https://doi.org/10.1016/j.ijggc.2020.103017

Haque F, Santos RM, Chiang YW (2020) Optimizing inorganic carbon sequestration and crop yield with wollastonite soil amendment in a microplot study. Front Plant Sci. https://doi.org/10.3389/fpls.2020.01012

Harley AD, Gilkes RJ (2000) Factors influencing the release of plant nutrient elements from silicate rock powders : a geochemical overview. Nutr Cycl Agroecosyst 56:11–36. https://doi.org/10.1023/A:1009859309453

Hinsinger P, Bolland MDA, Gilkes RJ (1995) Silicate rock powder: effect on selected chemical properties of a range of soils from Western Australia and on plant growth as assessed in a glasshouse experiment. Fertil Res 45:69–79. https://doi.org/10.1007/BF00749883

Israeli Y, Emmanuel S (2018) Impact of grain size and rock composition on simulated rock weathering. Earth Surf Dyn 6:319–327. https://doi.org/10.5194/esurf-6-319-2018

Jariwala H, Haque F, Vanderburgt S et al (2022) Mineral–soil–plant–nutrient synergisms of enhanced weathering for agriculture: short-term investigations using fast-weathering wollastonite skarn. Front Plant Sci 13:929457

Jarrell WM, Beverly RB (1981) The dilution effect in plant nutrition studies. In: Brady NC (ed) Advances in agronomy. Elsevier, Amsterdam, pp 197–224

Jeffery S, Abalos D, Prodana M et al (2017) Biochar boosts tropical but not temperate crop yields. Environ Res Lett 12:053001. https://doi.org/10.1088/1748-9326/aa67bd

K+S Minerals and Agriculture (2022) Patentkali® technical data sheet Version 9.2

Kantola IB, Masters MD, Beerling DJ et al (2017) Potential of global croplands and bioenergy crops for climate change mitigation through deployment for enhanced weathering. Biol Lett. https://doi.org/10.1098/rsbl.2016.0714

Kelland ME, Wade PW, Lewis AL et al (2020) Increased yield and CO2 sequestration potential with the C4 cereal Sorghum bicolor cultivated in basaltic rock dust-amended agricultural soil. Glob Change Biol 26:3658–3676. https://doi.org/10.1111/gcb.15089

Kuznetsova A, Brockhoff P, Christensen R (2017) lmerTest package: tests in linear mixed effects models. J Stat Softw 82(13):1–26. https://doi.org/10.18637/jss.v082.i13

Laboski CAM, Kelling KA (2007) Influence of fertilizer management and soil fertility on tuber specific gravity: a review. Amer J of Potato Res 84:283–290. https://doi.org/10.1007/BF02986240

Lefebvre D, Goglio P, Williams A et al (2019) Assessing the potential of soil carbonation and enhanced weathering through Life cycle assessment: a case study for Sao Paulo State, Brazil. J Clean Prod 233:468–481. https://doi.org/10.1016/j.jclepro.2019.06.099

Lenth R (2022) Emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.7.2. https://CRAN.R-project.org/package=emmeans

Ma JF, Yamaji N (2006) Silicon uptake and accumulation in higher plants. Trends Plant Sci 11:392–397. https://doi.org/10.1016/j.tplants.2006.06.007

Manning DAC, Theodoro SH (2020) Enabling food security through use of local rocks and minerals. Extr Ind Soc 7:480–487. https://doi.org/10.1016/j.exis.2018.11.002

Mikkelsen RL (2007) Managing potassium for organic crop production. HortTechnology 17:455–460. https://doi.org/10.21273/HORTTECH.17.4.455

Mohammed SMO, Brandt K, Gray ND et al (2014) Comparison of silicate minerals as sources of potassium for plant nutrition in sandy soil. Eur J Soil Sci 65:653–662. https://doi.org/10.1111/ejss.12172

Neu S, Schaller J, Dudel EG (2017) Silicon availability modifies nutrient use efficiency and content, C:N: P stoichiometry, and productivity of winter wheat (*Triticum aestivum* L.). Sci Rep 7:40829. https://doi.org/10.1038/srep40829

Panique E, Kelling KA, Schulte EE et al (1997) Potassium rate and source effects on potato yield, quality, and disease interaction. Am Potato J 74:379–398. https://doi.org/10.1007/BF02852777

Piepho HP, Edmondson RN (2018) A tutorial on the statistical analysis of factorial experiments with qualitative and quantitative treatment factor levels. J Agron Crop Sci 204:429–455. https://doi.org/10.1111/jac.12267

Puppe D, Sommer M (2018) Chapter one - experiments, uptake mechanisms, and functioning of silicon foliar fertilization—a review focusing on maize, rice, and wheat. In: Sparks DL (ed) Advances in agronomy. Academic Press, Cambridge, pp 1–49

Ramos CG, Querol X, Celimar A et al (2017) Evaluation of the potential of volcanic rock waste from southern Brazil as a natural soil fertilizer. J Clean Prod 142:2700–2706. https://doi.org/10.1016/j.jclepro.2016.11.006

Ramos CG, Hower JC, Blanco E et al (2021) Possibilities of using silicate rock powder: an overview. Geoscience Frontiers 13:101185. https://doi.org/10.1016/j.gsf.2021.101185

Rudnick RL, Gao S (2003) Composition of the Continental Crust. In: Treatise On Geochemistry. Elsevier Ltd., pp 1–64

Sarkar SR (2021) Glacial rock flour: its characteristics and enhanced weathering. PhD Thesis, University of Copenhagen

Song Z, Müller K, Wang H (2014) Biogeochemical silicon cycle and carbon sequestration in agricultural ecosystems. Earth Sci Rev 139:268–278. https://doi.org/10.1016/j.earscirev.2014.09.009

Sørensen NKK, Bülow-Olsen A (1994) Fælles arbejdsmetoder for jordbundsanalyser. Landbrugsministeriet Plantedirektoratet

Stark J, Westermann D, Hopkins B (2004) Nutrient management guidelines for russet burbank potatoes. University of Idaho, Collage of Agricultural and Life Sciences

Statistics Denmark (2021) Harvest by region, crop and unit. https://statbank.dk/HST77

Taylor LL, Quirk J, Thorley RMSS et al (2015) Enhanced weathering strategies for stabilizing climate and averting ocean acidification. Nat Clim Chang 6:402. https://doi.org/10.1038/nclimate2882

Torabian S, Farhangi-Abriz S, Qin R et al (2021) Potassium: a vital macronutrient in potato production—a review. Agronomy 11:543. https://doi.org/10.3390/agronomy11030543

Tubana BS, Babu T, Datnoff LE (2016) A review of silicon in soils and plants and its role in us agriculture: history and future perspectives. Soil Sci 181:393–411. https://doi.org/10.1097/SS.0000000000000179

Van Straaten P (2002) Rocks for crops: agrominerals of sub-Saharan Africa. International Centre for Research in Agroforestry, Nairobi

Vienne A, Poblador S, Portillo-Estrada M et al (2022) Enhanced weathering using basalt rock powder: carbon sequestration, co-benefits and risks in a mesocosm study with *solanum tuberosum*. Front Clim 4:869456. https://doi.org/10.3389/fclim.2022.869456

Violante A, Caporale AG (2015) Biogeochemical processes at soil-root interface. J Soil Sci Plant Nutr 15:422–448. https://doi.org/10.4067/S0718-95162015005000038

Wang JG, Zhang FS, Cao YP, Zhang XL (2000) Effect of plant types on release of mineral potassium from gneiss. Nutr Cycl Agroecosyst 56:37–44. https://doi.org/10.1023/A:1009826111929

White PJ (2013) Improving potassium acquisition and utilisation by crop plants. J Plant Nutr Soil Sci 176:305–316. https://doi.org/10.1002/jpln.201200121

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.