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Supplementary Materials: Glacial Rock Flour as Soil Amendment in Subarctic Farming in South Greenland

Frederik Næsby Sukstorf, Ole Bennike and Bo Elberling

S1. Collecting Glacial Rock Flour (GRF) in Tasersuaq

A field campaign was carried out on lake Tasersuaq in August 2018, aiming to map the vast glacial rock flour reserve believed to exist here, as part of the three-year research program on glacial rock flour as part of a collaboration between several research institutes. Tasersuaq is a large lake situated at roughly 65.1 °N and 50.8 °W, 100 km northeast of Nuuk, the capital of Greenland.

The field work consisted of a seismic survey and sediment sampling, both in terms of bed surface sediments and cores, aiming to yield clues on the extent of the glacial rock flour deposits and sediment properties. A total of 63 surface samples were collected using a van Veen grab sampler. A vibrocorer (VibeCore-D, developed by SDI Specialty Devices) was used to retrieve seven cores ranging in length from 0.5 to 2 m with a diameter of 7.6 cm. All sediment sampling was conducted from a coring platform equipped with a 4 m high tripod with a winch, which was used to retrieve samples from the lake floor. Sediment samples were collected throughout the lake; however, due to technical difficulties and more accessible water depths, most of the sampling was concentrated in the southern part (Figure S1).

The seismic survey was conducted using a small speedboat equipped with a C-Boom as the seismic source and a streamer to record the reflected signal, yielding a resolution of 30 cm and a lake floor penetration of approximately 50 m. Relative shallow water depths are seen in the southern and northern parts, whereas the central part of the lake is up to 177 m deep (Figure S1B). The sediment thickness depends on the water depth, and the deepest parts of the lake show sediment successions of >50 m (Figure S1C).

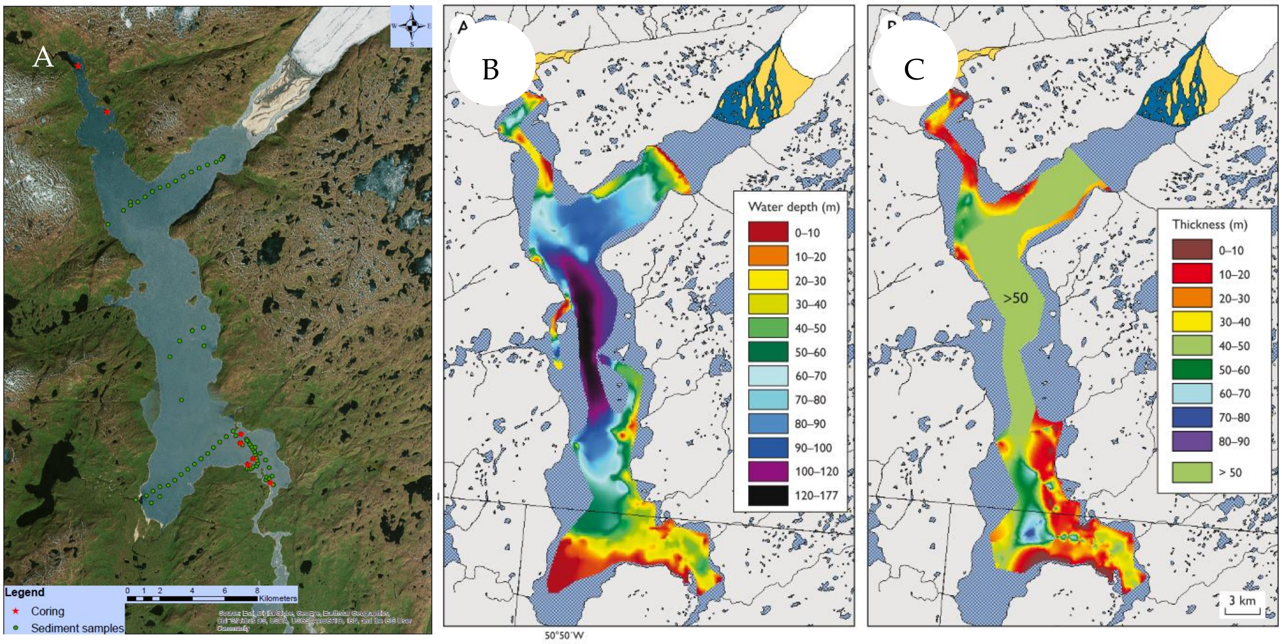


Figure S1. (**A**) An overview of the sampling area with green dots marking surface sediment samples and red stars denoting coring sites. (**B**) Bathymetry of Tasersuaq. (**C**) Sediment thickness. Note that the scale extends to above 50 m of sediment thickness, but as the boomer signal could not further penetrate the sediment, exact measures were not available (Bennike et al. 2019).

S2. Rock Flour Treatment

The material sampled in lake Tasersuaq in August 2018 was used for the field experiment conducted in this study. After returning to Copenhagen, the cores were split, and the one half was used for X-ray fluorescence (XRF)-scanning and analysis of magnetic susceptibility, while the other half was stored indoor covered in plastic film to prevent drying. Afterwards, the halved cores were emptied into aluminum trays and dried at 105 °C for 24 hours.

After drying, the material, in total approximately 61 kg of rock flour, was kept in closed plastic bags. Since the process of drying resulted in the material clumping together in dense chunks, it was necessary to break the clumps into size fractions more suitable for soil application. At first, the material was coarsely broken down, after which small portions were gradually crushed with mortar and pestle and sieved in a 2 mm sieve. The resulting product was a powder containing aggregates of a wide range of sizes below 2 mm, as well as single particles (Figure S2).

Figure S2. Pictures of the crushing procedure. (**A**) An example of the rock flour after the initial crushing. (**B**) The material after further crushing and sieving.

Prior to mixing, homogenizing and distribution in the field, the homogeneity of the material was tested by analyzing randomly picked subsamples for particle size, pH, and exchangeable base cations.

The results of laboratory analyses of Tasersuaq rock flour with regards to its merits as agriculture application revealed that the rock flour contained a range of macro- and micronutrients (except nitrogen), albeit in small concentrations. The material was found to have a large surface area and a median particle size of 5.5 µm, as well as a neutral pH ($CaCl_2$) of 6.9. This glacial rock flour (GRF) also has the advantage of being deposited in a freshwater environment, so it was not necessary to thoroughly wash out the high content of NaCl found in marine deposits.

In order to make sure that the material was thoroughly homogenized prior to being distributed, it was carefully mixed in a large plastic container, after which the material was laid out on a plastic tarp, mixed, and divided into stacks of equal size by continuously halving the stacks until the desired sample size of 2 kg was attained, yielding, in total, 30 bags. This procedure was applied to ensure a high degree of homogeneity between samples. Due to an inadequate weight range on the laboratory scales, the bags were weighed on an ordinary bathroom scale with an accuracy of ± 100 g, meaning that small imprecisions between sample mass can be expected. Another challenge regarding the procedure of mixing and distributing the material was that the very fine particles tended to considerably dust when handled, removing an unknown (albeit probably small) fraction of the very fine-grained material. The dusting was sought minimized by limiting handling; however, it was not possible to entirely eliminate, adding to the inaccuracies associated with this procedure.

Once the rock flour had been distributed in bags of 2 kg, they were closed, packed in transport boxes, and shipped to Narsarsuaq.

S3. Field Experiment—Physical Setting and Design

Another field campaign was carried out during the summer of 2019, this time with the objective to test the effect of applying glacial rock flour in Greenlandic agriculture. The field work took place on a sheep farm, Ipiutaq (lat.: 60°58.468 'N, long.: 45°42.710 'W) located halfway between Narsaq and Narsarsuaq at the shore of Tunulliarfik. This place was chosen for two reasons: Firstly, the area is easily accessible by boat from Narsarsuaq, and secondly, The University of Copenhagen has had several researchers do field work there, so a good contact was already established.

The farm comprises approximately 250 ewes and lambs, whose food comes from two sources. During summer, the sheep roam the surrounding area foraging/grazing on the vegetation. The sheep are gathered during September, and the majority of the lambs are sent to the slaughterhouse, while the ewes are kept in stables during winter, feeding on locally produced hay and occasionally imported coarse fodder elements. The hay for feeding is produced on the farm's approximately 11 ha of land, with the crops being a combination of cereals (mainly oat) and a mixture of grasses (both perennial and annual).

The farmland is situated in a gently sloping area bordering the coastline. The uphill fields are fairly steep and face south, whereas the lower fields are less steep. The fields range in size from 0.02 to 1 ha. A common characteristic of the farmland (and agricultural fields in Greenland in general) is that the soil contains a vast amount of rocks of different sizes, ranging from pebbles to boulders, so preparing new soil for cultivation is a laborious task. This characteristics has also implications for the general cultivation and tillage practices, because plowing is impossible in many areas and tillage may be limited to harrowing.

The fertilizing scheme consists of applying regular granulated nitrogen, phosphorus and potassium (NPK)-fertilizer in the early summer, aiming for 110 kg N ha^{-1}. Fertilizers of varying chemical composition were used, the most common being 17:7:13, which was also the fertilizer utilized in the field experiment. The nutrient content in weight percent and application per hectare is seen in Table S1. To attain 110 kg N ha^{-1} y^{-1} (which, according to the farmer, is the general fertilizing scheme for perennial grass) with the presented mineral composition, approximately 650 kg of fertilizer per hectare were used.

Table S1. Nutrient composition of applied fertilizer.

Element	Wt%	Application per hectare [kg]
Total N	16.6	108
NO_3	5.3	35
NH_4	11.3	73
P	6.6	43
K	13.6	88
S	2.4	16
Mg	0.2	1

S4. Experimental Design

A field experiment was established on the northernmost field, a gently southward sloping patch with an area of 0.02 ha, aiming to investigate the first-year effect of the addition of glacial rock flour on the yield of perennial grass in Greenland. The field had been sowed with a grass mixture, consisting mainly of timothy grass (*Phleum pratense*) but including other grass species (Table S2), in the spring of 2018. At the time of the experiment, the field consisted almost exclusively of timothy grass, as the other species presumably had subsided due to being less winter-hardy. Timothy grass is a very winter-hardy, perennial grass that is adapted to the cool and wet climate of the northern U.S., where it is widely grown, as well as in northern Europe. It is regarded as a high-quality feed, mostly for haymaking. Its shallow, compact, and fibrous root system leads to low drought resistance, requiring an effective precipitation of 450 mm y^{-1} for optimal growth (USDA, 2009).

Table S2. Grass varieties in seed mix.

Variety	Percent
Timothy (*Phleum pratense*)	75
Red fescue (*Festuca rubra*)	15
Common bent (*Agrostis capillaris*)	5
Kentucky bluegrass (*Poa pratensis*)	3
Smooth brome (*Bromus inermis*)	2

A rectangular area of 8 x 5 m, its boundaries demarcated by iron rods inserted into the soil, was laid out in the field. This 40 m^2 plot defined the area on which the experimental design was conducted. Figure S3 shows the approximate position of the experimental plot on the farm.

In order to attain a rectangle with four right angles, the two diagonals of the rectangle were measured at 9.4 m ($\sqrt{5^2 + 8^2} = 9.43$).

The applied experimental design consisted of forty 1 m^2-plots arranged in a checkerboard pattern as a randomized block design (Dyke, 1974). Each 1 m^2 plot was measured by utilizing the fact that the two diagonals of each square should measure 1.4 m. Only twenty of the plots were treated, and in order to avoid rim effects, treated plots were arranged with only corners touching. Figure 6 presents a sketch of the experimental design. Plots were randomly distributed to prevent any systematic bias due to spatial differences in the field.

Figure S3. Unmanned aerial vehicle image showing an overview of the farm, with the red star marking the approximate position of the experimental field.

The experiment considered treatments of different combinations of glacial rock flour and fertilizer additions (Table S3). Treatment 1 considered the effect of no added fertilizer—only with background soil nutrients. Treatment 2 considered the effect of adding a high amount of GRF (40 t ha^{-1}) without any other additives. Treatment 3 involved an addition of 25 % NPK fertilizer plus 20 t GRF per hectare. The fourth treatment comprised 40 t GRF per hectare plus an addition of 25 % of regular NPK fertilizer.

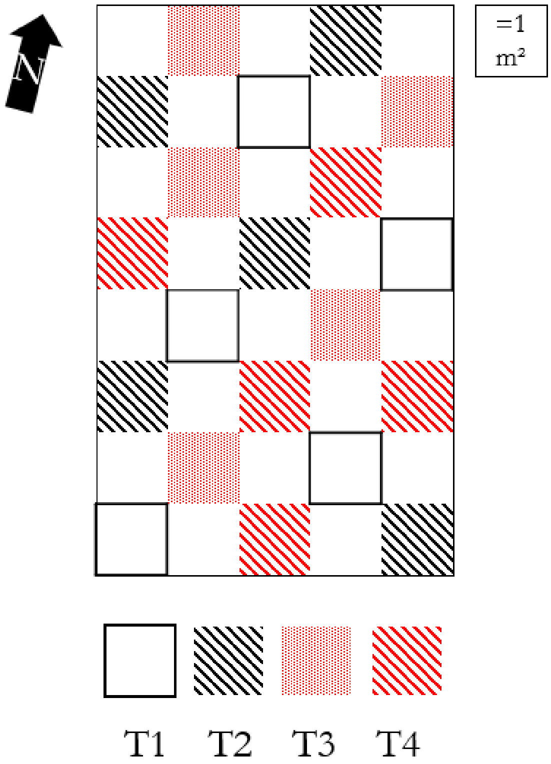


Figure S4. Conceptual plan view of the experimental setup.

Table S3. Specifications on applied experimental treatments. GRF: glacial rock flour.

Treatment	N [kg ha^{-1}]	P [kg ha^{-1}]	K [kg ha^{-1}]	GRF [kg ha^{-1}]	No. of plots
T1	0	0	0	0	5
T2	0*	3.3*	1.0*	40 000	5
T3	27.5**	13.0**	21.5**	20 000	5
T4	27.5**	14.6**	22.0**	40 000	5
(*) Nutrients supplied from GRF only. (**) Nutrients from both GRF and fertilizer					

As stated earlier, the typical fertilizing scheme is to apply 650 kg NPK per hectare, so 162.5 kg ha^{-1} had to be applied for treatments 3 and 4, which resulted in 16.3 g of fertilizer per m^2. Likewise, to reach the equivalent value of 40 and 20 t GRF per hectare, 4 and 2 kg m^{-2} had to be applied. The application of a reduced amount of fertilizer as compared to regular practices owed to the objective of the experiment to test the effect of rock flour application. Abundant fertilization would likely dominate compared to the effect of rock flour treatment, assigning any significant differences to the fertilizer.

The plots were treated on 4 June by emptying each bag, which contained either just rock flour or a mixture of rock flour and pelletized fertilizer, onto the plot in question, after which the material was raked to distribute it evenly in the plot (Figure S5a). The procedure was carried out during low wind conditions (mean wind = 2.2 m s^{-1} from SW), minimizing the loss of fine-grained particles.

Shortly after the experiment had commenced, a sprinkler irrigation system and a rain gauge were established on the field (Figure S5b). After three hours of irrigation, the sprinkler was stopped, and the rain gauge measured at 10 mm. However, as the water pressure had dropped at some point during the irrigation period, the sprinkler was not distributing water evenly when it was approached after the three-hour period. As seen in Figure S5a, the rock flour lied as a relatively thick layer on top of the soil immediately after being spread; nevertheless, it can be seen in Figure S5b that a large fraction seemed to have dissipated as a result of the irrigation.

(**A**)

(**B**)

Figure S5. (A) The experimental field immediately after the start of the experiment. (**B**) The field after three hours of irrigation from the sprinkler seen in the middle of the image. Notice the rain gauge just south of the sprinkler. Both images were taken on 4 June 2019. The direction of view is approximately north.

S5. Field Sampling

Soil Profile in the Experimental Field

In order to evaluate the effect of applying soil amendments, knowledge of soil properties prior to the experimental setup was crucial. Hence, a soil profile was dug on 1 June 2019 in the experimental field ,and soil samples were taken in order to evaluate soil characteristics such as bulk density, texture, pH, and nutrient status. Samples were taken by inserting cylinder rings with a known volume of 86 cm^3 into the soil profile, using a canister that was horizontally hammered into the soil to avoid compaction. Samples were sought where soil horizons were evident. A total of four soil samples were taken. Figure S6A shows an example of how samples were retrieved. Samples were stored in plastic bags a 5 °C until further analysis. Several attempts to dig a suitable soil profile were made, though these were halted by the presence of large rocks that are also evident in the successful profile shown in Figure S6B. At approximately 40 cm of depth, further progress was impeded by a layer consisting of gravel and rocks, and so the deepest sample was taken here.

(**A**) (**B**)

Figure S6. Images of the soil profile dug in the experimental field. (**A**) A close up showing the soil sampling procedure. (**B**) Soil profile—notice the large rocks in the bottom and to the right of the measuring stick.

Soil Sampling in Plots

Soil sampling was conducted in selected T1 and T2 plots after the plots had been harvested in August, with the aim to investigate whether the application of rock flour had any measurable impact on selected soil properties. This was done by vertically inserting a cylindrical sample ring (v = 86 cm^3) into the soil, retrieving a sample of the topmost 4 cm of the soil, an example of which is shown in Figure S7A. Afterward, the soil surrounding the ring was removed to enable further insertion, and another sample was taken directly on top of the former. In this way, a column of the top 8 cm of the soil was sampled and separated into two subsamples. An example of a top sample from T2 is shown in Figure S7B. Notice the layer of rock flour on top of the sample that is seemingly not integrated into the soil.

(A) (B)

Figure S7. An example of the soil sampling procedure. (**A**) Vertically inserted sample ring. (**B**) A soil sample showing the GRF concentrated at the top.

Upon return to Copenhagen, soil samples were dried at 60 °C for 24 hours. A small subsample of ~2 g from all the soil samples was milled using an agate ball mill on a shaking platform before analyses of total carbon and nitrogen content, and the remainders of each sample were then dry-sieved at 2 mm to obtain material for chemical analyses.

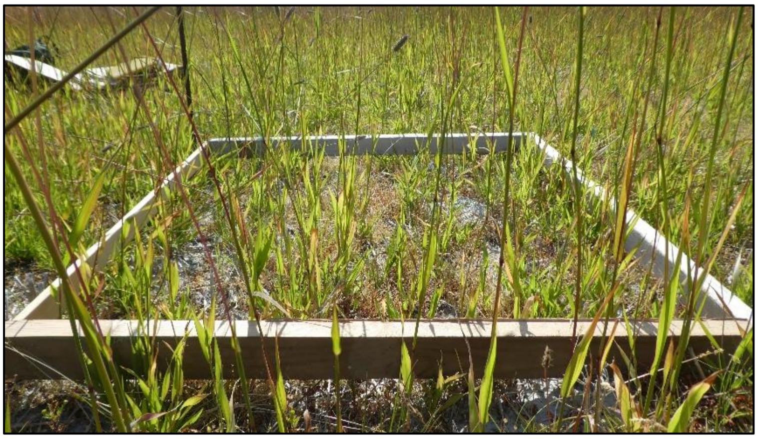
Aboveground Biomass Sampling

The sampling of biomass from the experimental plots was carried out 80 days after the treatments had been applied during the period from 21 to 23 August (Figure S8). The biomass of the aboveground biomass (AGB) fraction of the plants in the treated plots was determined by the harvest technique, where vegetation is cut according to a quadrat of a given size in each plot, as described by, e.g., Brummer et al. (1994) and Franks and Goings (1997). This method of AGB determination yields the most accurate and direct estimate of AGB compared to the range of non-destructive methods. It is, obviously, destructive and thus not suitable for all types of research in biomass (e.g., forest and, protected areas). After harvesting, the plant material should be dried at, preferably, 60 °C for approximately 24 hours, depending on the nature of the material. The dry weight is hereafter recorded, as the water content of fresh plant material is highly variable during the day and between plant species.

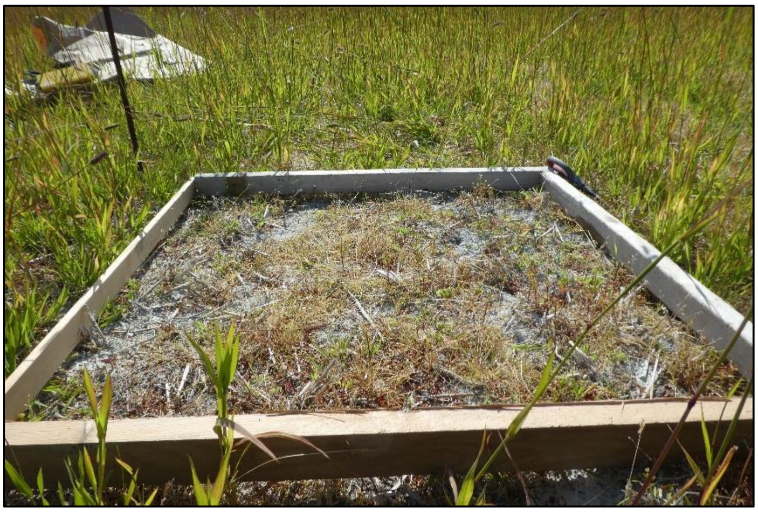
A range of choices must be made and kept equal for the experiment regarding quadrat size, clipping height, the separation of living and dead biomass, and whether to omit or retain biomass from other species than the sought (e.g., weeds) to ensure comparability between plots.

Figure S8. The experimental field on 21 August from the same point of view as in Figure S5.

For this experiment, a quadrat of 0.7 × 0.7 m (= 0.49 m^2) was placed in the middle of a given plot (Figure S9), and all cultivated plants were cut with clippers as close to the soil surface as possible, avoiding any unwanted plant material from weeds, etc. It is extremely difficult to completely avoid gathering unwanted species or dead plant matter, as well as to avoid dropping tiny amounts of clipped plants; however, these uncertainties were assumed negligible.



(**A**)



(**B**)

Figure S9. (**A**) Placement of the sampling quadrat before cutting. (**B**) The quadrat after sampling of aboveground biomass (AGB).

After harvesting, the grass samples were put into paper bags, marked, and dried in the barn. Though not the optimal drying scheme, as no oven was available during the week of field work, this procedure was necessary. Upon return, the grass samples were first coarsely clipped and then loosely packed in aluminum foil packages with holes to allow water vapor to escape. The packages were then weighed and oven-dried for 24 hours at 60 °C with a fan blowing. A check for constant weight was carried out by weighing one of the packages once every hour during the last four hours of drying, observing that the weight change per hour amounted to less than the range of the scale (0.01 g), thus indicating that all moisture had evaporated. After drying, the packages were left at room temperature for an hour before weighing to allow the plant matter to rehydrate according to ambient water vapor. Therefore, a small increase in weight was observed between the last control weight and the final weight.

To determine the elemental composition of the harvested plant matter, a representative subsample of approximately 10 g from each sample was taken that was comprised of all plant parts, i.e., stems, leaves, and flowers, to be milled. Milling was done at UC's Department of Plant and Environmental Sciences. Samples were put in 250 ml plastic bottles, and three zirconium oxide grinding balls were placed in each bottle. The bottles were then fitted in a rack and shaken in a paint shaker in laps of 4.5 minutes for a total of 45 minutes until a powdery substance was attained.

It should be noted that the plant samples were not washed prior to being analyzed for elemental composition, so the samples may have been slightly contaminated by, e.g., dust. However, since there was a rather large rainfall event four days before the harvest, contamination was considered negligible.

References

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