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REGULAR ARTICLE

Addition of a volcanic rockdust to soils has no observable effects on plant yield and nutrient status or on soil microbial activity

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Abstract
Background and Aims Rising costs and pressure on supplies of commercial mineral fertilizers and increasing markets for organically produced foods and feeds have led to a growing interest in soil amendments to supply plant nutrients. Rockdust is a by-product of quarrying and its effectiveness to supply plants with nutrients has been a contested issue and there have been no assessments of its effect on soil biota other than plants. The aim of this study was to assess the effect of a commercially-available volcanic rockdust application on crop growth and element concentrations for a wide range of macro and microelements and the response of soil microbial communities to rockdust due to the potential alteration in soil mineralogy.
Methods A three-year controlled outdoor-growing experiment was conducted on three different soil types with two wheat cultivars in the first year following rockdust application and with forage species in the third year.
Results Our results show that the tested rockdust had no positive or negative effect on plant growth or nutrient composition. In addition, the microbial response to added substrates, a sensitive measure of changes in soil environment, were unaltered by the rockdust.
Conclusions As the rockdust had no nutrient or toxic effect it can probably be considered as an inert material which at least causes no harm but equally has no demonstrable ecological or agricultural benefit.

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Introduction

Rockdust, widely available as a by-product of quarrying operations has received increasing interest as a low cost, locally available soil amendment. The primary idea is that most nutrients in the natural environment, the main exception being N, are derived ultimately from the weathering of rock-forming minerals. Part of the interest is driven by the organic sector seeking suitable soil amendments that meet organic growers' criteria but also conventional farming anticipates growing pressure to source nutrients locally in more sustainable ways (Manning 2010). Fresh rockdusts from quarrying operations consist of a wide range of fine to coarse particle sizes, and depending on rock type, various minerals may occur. The mineralogy of a rock dictates not only the chemical elements present but crucially the molecular form and chemical bonding environments in which those elements occur. Form is paramount to determining the rate at which an element may become plant available as a result of release from the mineral by weathering, although many other factors such as particle size and interactions with organisms can also play key roles in determining the rates of these processes (Van Straaten 2006; Wilson 2004). Thus the potential nutrient supplying capacity of any given rockdust is a function of its mineralogy. It follows that different types of rocks may have widely varying potentials as soil amendments although such potential ought to be broadly predictable based on knowledge of the relative ease with which the minerals present in a rock are known to weather and some rock types would be expected to have more potential than others.

As far as specific nutrients are concerned, there is some evidence of the use of rock powders as fertilizers to supply potassium (K) (Baerug 1991a; Bakken *et al*. 2000; Coroneos *et al*. 1996), magnesium (Mg) (Baerug 1991b), phosphorus (P) (Stamford *et al*. 2005) and some other elements (Weerasuriya *et al*. 1993). Barak *et al*. (1983) reported significant improvement in iron (Fe) nutrition of peanuts grown in pots of highly calcareous soil by treating the pots with different amounts of ground basalt and tuff. Granite powder has also been shown to act as a slow-release K fertilizer to two pasture species grown in a greenhouse pot experiment (Coroneos *et al*. 1996). However, there are other studies which dispute the benefits of applying rockdust as a fertilizer (Bakken *et al*. 2000; Bolland and Baker 2000). Since most types of rockdust would be considered as a relatively slow-release source of elements (compared to highly soluble conventional fertilizers), an important factor in its effectiveness in providing plants with nutrients is assumed to be its particle size, which determines its specific surface area, i.e. a crucial rate determining parameter for weathering. It is important also to consider the length of time since the rockdust was added to the soil and the appropriate time scale for assessing any effects (e.g. Sanz Scovino and Rowell 1988).

Like plants, soil microorganisms are also dependent on the nutrients available in soil (Uroz *et al*. 2009). Microbial communities in soils are comprised of a large diversity of species and perform key functions. Functional diversity as a component of overall diversity in soils, provides a practical and ecologically relevant measure of microbial diversity (Degens *et al*. 2001; Zak *et al*. 1994), and has been suggested as a sensitive means of assessing soil quality (Ritz *et al*. 2009). One approach that has proved sensitive is to assess the community-level physiological profiles (CLPP) of whole communities through measurement of the use of a range of carbon (C) substrates as substrate induced respiration (SIR) and in particular using the MicroResp technique (Campbell *et al*. 2003; Chapman *et al*. 2007). The structure of microbial communities in soil is affected by the bio-physico-chemical characteristics of soil, among which nutrient availability is an important factor (Carson *et al*. 2007) so we can hypothesize that minerals added to soil will alter microbial communities and their activity. In environments of very low nutrient concentrations, evidence has been presented that microorganisms preferentially colonize and dissolve feldspars that contain limiting nutrients (Rogers and Bennett 2004). In another study, it was shown that quartz - which is a form of pure silica and also rather resistant to weathering - had a less complex bacterial community structure than other (possibly more weatherable) minerals (Gleeson *et al*. 2006). Furthermore, Certini *et al*. (2004) showed that rock fragments present in soil, support a different microbial assemblage compared to the fine earth of the surrounding bulk soil. Thus, mineralogy may play a role in microbial abundance and viability in many environments (Rogers and Bennett 2004). The influence of altering the mineral composition of soil on microbial community composition has been investigated in only a few studies, e.g. by Carson *et al*. (2009; 2007). However, all of the foregoing studies focused on the relationship between microbial colonization and 'major' element constituents of different minerals, whilst the minerals' content of trace elements, mainly micronutrients, e.g. manganese (Mn), zinc (Zn), and cobalt (Co) needed by rhizobia (O'Hara 2001; O'Hara *et al*. 1988), may also be influential in this aspect. So far, there seems not to have been any research on how microbial communities of soil can be influenced by rockdust when it is applied as a soil amendment.

Manning (2010) has emphasized that testing the use of rockdust as a source of nutrients, requires both biology and mineralogy. Therefore, the overall aim of this study was to evaluate the effects of applying a commercially available 'volcanic' rockdust to three different soil types in relation to both crop growth and off-take (amount of elements -by weight- taken off the soil), of macro and micronutrients as well as assessing any effects on the soil microbial communities and to relate potential effects to the mineralogy of the rockdust. The specific objectives were to study (i) the soil chemical response, and (ii) the influence on the soil microbial communities as reflected by alteration in the mineralogy of the soils after applying rockdust, (iii) the yield and macro and micronutrient concentrations in grain of two spring wheat cultivars in the first year after rockdust application (short-term effect), and (iv) in ryegrass and red clover, grown as a mixed stand, three years after the rockdust treatment (long-term effect). We hypothesized that the addition of large amounts of rockdust after 3 years of weathering in soil would increase plant growth and nutrient status and increase microbial responses to added carbon substrates.

Materials and methods

Rockdust and soils

Commercially available'volcanic'rockdust (SEER Center, Perthshire, Scotland) as well as three different soil types were used for the test. SEER Center rockdust is obtained from Collace quarry (Kinrossie, Perthshire) and is widely available throughout the UK and via international distributers. Soils were namely a horticultural peat bought from a commercial garden center, a loamy sand and a clay soil from the plough layer (Ap horizon) of arable fields in Uppsala (N 59° 49′,E 17° 39′), Sweden. Characteristics of the rockdust and soils are shown in Table 1.

Experimental treatments

Rockdust was mixed with the soils at two application rates; 5 kgm^{-2} (the highest rate recommended by the supplier) and 0.5 kgm^{-2} (the lowest rate recommended by the supplier) i.e. equal to 50 tha^{-1} and 5 tha^{-1}, respectively. As a control treatment, the soils were also mixed with an assumed inert and pure (as verified by XRD analysis) quartz sand at the 5 kgm^{-2} rate. This was done in order to physically manipulate the control treatment in the same manner as the rockdust treatments by replicating the mixing. Plastic growth boxes (36×55×25 cm) were filled with the appropriate treatments in a randomized block design with four replications and placed outdoors in a netted area, in Uppsala, Sweden. The boxes were planted with one of two cultivars of spring wheat, *Triticum aestivum* L. (cv. Ölandsvete an old Swedish cultivar, not commercially bred and cv. Triso, a modern Swedish cultivar) in the first year (2007) without any further nutrient applications and left fallow in the second year. The two cultivars were included to investigate the possibility of different concentrations of nutrients and trace elements in grains, i.e. quality, in an older cultivar compared to a modern high producing cultivar. Half of the boxes from the first year (all from the cv. Ölandsvete) were sown with mixed stands of perennial ryegrass (*Lolium perenne* L., cv. Helmer) and red clover (*Trifolium pratense* L., cv. Nancy) in the third year (2009). All boxes were fertilized with ammonium nitrate (equivalent to 30 $kgha^{-1}$ of N) twice during the growing season of the third year. Boxes were watered with tap water in the first year and with distilled water fed by plastic pipes in the third year.

Harvests and analyses

Grains of the two cultivars of wheat harvested at their maturity, as well as the biomass of the forage species harvested at the stem elongation stage to a stubble height of *approx.* 5 cm, were dried at 50 °C and weighed. The wheat grains were wet digested with concentrated HNO_3 as whole grain as described by Wångstrand *et al*. (2007) and analysed for calcium (Ca), K, Mg, sodium (Na), P and sulphur (S) by ICP-Optima 7300 DV (Perkin Elmer SCIEX, Waltham, MA, USA) and for cadmium (Cd), Co, chromium (Cr), copper (Cu), Fe, Mn, molybdenum (Mo), nickel (Ni), lead (Pb) and Zn by ICP-MS

Table 1 Carbon and nitrogen concentration, pH-H_2O and particle size distribution in rockdust and original soil samples

Rockdust and soils	C	N	Liming effect [a]	pH	Particle size distribution (%)[b]							
	%DW		% CaO		<2 μm	2–6 μm	6–20 μm	20–60 μm	60–200 μm	200–600 μm	600–2000 μm	>2000 μm
Rockdust	0.10	0.01	1.9	9.1	2	2	5	7	10	14	30	30
Clay	2.13	0.23		6.9	63	17	9	5	3	3	0	0
Loamy sand	1.33	0.09		6.3	9	2	4	3	10	58	14	0
Peat[c]	29.2	1.16		6.8								

[a] 2 g of rockdust was shaken with 50 ml 1 M HCl for 75 min, diluted to 500 ml and filtered, whereafter surplus acid was titrated with 0.1 M NaOH (Kungl. Lantbruksstyrelsen 1950)

[b] Analysed as described by Ljung (1987)

[c] Low-humified sphagnum 75%v, highly-humified sphagnum 20 % v, sand 5 % v at the time of purchase

ELAN 6100 DRC (Perkin Elmer SCIEX, Waltham, MA, USA) as described by Dahlin *et al*. (2012). Ryegrass and red clover samples were milled to a particle size below 1 mm, before further analyses, using a cutting mill (Grindomix GM 200, Retsch GmbH) with a titanium knife and a plastic container to avoid microelements contamination (Dahlin *et al*. 2012). Macro and microelement concentrations in forage species samples were determined by wet digestion using concentrated HNO_3 (Dahlin *et al*. 2012) and analysed as described above. Total C and N were measured on a LECO CN-2000 element analyser (Leco Corporation, St. Joseph, MI, USA) using 30 mg of fine ground grain/plant samples, heated at 1050 °C for 5 min. Certified reference materials (NCS Maize Flour, China National Analysis Center for Iron and Steel 2008; and NIST Rice Flour, National Institute of Standards and Technology, Geitersburg, MD, USA) were included in all batches. Off-take of the elements by the harvested plant materials was calculated as mixed stands of ryegrass and red clover and reported per square meter.

Soil analyses

Representative soil samples were taken from each growth boxes after harvesting forage species at the end of the growing season year 3. Soil samples were subdivided and 1) air dried and sieved to <2 mm for chemical analyses; 2) air dried for mineralogical analyses and 3) stored fresh at 4 °C for biological analyses.

Chemical analyses

For pH-H_2O measurement, 25 ml deionized water was added to 5 g of soil, shaken in an end-to-end shaker for 15 min and left to stand overnight. The soil suspensions were then shaken for 1 min just prior to measurement (Swedish Standards Institute 1997). Pseudo-total concentrations of macro and microelements in the soil samples were measured using nitric acid/hydrogen peroxide extraction as follows: 0.5 g sieved soil, digested with 5 ml concentrated HNO_3+0.5 ml 30 %-H_2O_2 in a closed teflon vessel in a micro wave oven and measured on ICP-SFMS (at ALS Scandinavia AB lab). EDTA-extractable microelements (Cd, Co, Cr, Cu, Mn, Mo, Ni, Pb, Zn) of the soil samples were measured using the method described by Streck and Richter (1997) with some modification, so that Na-EDTA was used and the extracts were analysed by ICP-MS ELAN 6100 DRC (Perkin Elmer SCIEX, Waltham, MA, USA). Total C and N of the soil samples were measured on a LECO CN-2000 element analyser (Leco Corporation, St. Joseph, MI, USA) using 1 g of finely ground soil heated at 1250 °C for 5 min. An in-house reference soil sample was included in the batches for quality assurance purposes.

Mineralogical analyses

For both qualitative and quantitative mineralogical analysis, 3 g of each air-dried soil sample was ground in an agate McCrone mill in ethanol for 12 min. Random powders were prepared for X-ray diffraction (XRD) analysis by spray drying the resulting slurries according to the procedure described by Hillier (1999). For quantitative analyses of the rockdust, the three soils and the quartz sand, XRD patterns were measured on spray dried samples run on a Siemens D5000 (Siemens, Germany) using Co K-alpha radiation selected with a graphite monochromator and the analyses made by a full pattern fitting method (Omotoso *et al*. 2006). Qualitative XRD analyses of spray dried samples were also made as part of the assessment of the change in mineralogy due to rockdust addition to the soil samples. These XRD patterns were recorded on a Panalytical Xpert Pro diffractometer (Panalytical, the Netherlands) using Ni filtered Cu K-alpha radiation.

Microbiological analyses

Potential differences in the microbial community composition of the soils in response to the treatments were examined by measuring the Community Level Physiological Profiles (CLPP). The physiological response was measured as the flush of carbon dioxide after the addition of different carbon sources (substrates), usually called the Substrate Induced Respiration (SIR), and was determined by the MicroResp™ method (Campbell *et al*. 2003). In brief, soil samples were sieved to <2 mm, adjusted to 30–40 % of water holding capacity (WHC) of the soils, and used to fill 96-well microtiter deep-well plates with a capacity of 1.2 ml (Thermo LifeScience, Basingstoke, United Kingdom). After 3–4 days of pre-incubation at 25 °C, solutions of sole C sources (namely arginine, L-alanine, α-ketoglutaric acid, L-arabinose, citric acid, L-cystein, D-fructose, D-galactose, γ-amino butyric acid, D-glucose, L-lysine, L-malic acid, N-acetyl-glucosamine, oxalic acid and trehalose) were added from freshly prepared solutions. After adding the substrates or deionized water (as a control) to the soils in the deep-well plates, CO_2 was trapped in a detection gel cast in a 96-well microplate cover. The detection plates were prepared using the indicator cresol red (12.5 ppm, wt/wt), potassium chloride (150 mM), and sodium bicarbonate (2.5 mM) set in 1 % Purified agar. The detection plates were read in a microtiter plate reader (VMAX; Molecular Devices, Wokingham, UK) at 570 nm immediately before and after 6 h of incubation at 25 °C. Substrate induced respiration data were calculated by subtracting the values of the CO_2 respired in the control (deionized water) from the respiration after addition of C sources (Campbell *et al*. 2003).

Statistical analyses

Analysis of variance (ANOVA) with Tukey pair-wise comparisons was used to assess treatment differences in the data of soil, grain and plant chemical analyses and SIR data from individual C sources, using JMP 9.0.0 (SAS Institute Inc., Cary, NC, USA) and $p<0.05$ as the limit for statistical significance. First, the full model including the factors soil, treatment, wheat variety (where applicable) and all two- and three- way interactions, was fitted. Blocks were also included as a factor in the model. When the interactions were not significant, the model was reduced to include main effects only. Where the residual variance was not homogeneous on the original scale, observations of soil, grain and plant were transformed before analysis, using Box-Cox transformation (Box and Cox 1964) and SIR data were log-transformed. Presented averages are back-transformed means.

Statistical analysis of CLPP data from all added C sources was based on Bray-Curtis dissimilarities of SIR data which were analysed by canonical variate analysis using the CAP program (Anderson and Willis 2003).

Results

Soils properties

Total C, N and pH of the soils (before treatment) as well as the rockdust applied in the experiment are shown in Table 1. Soils had similar pH, while rockdust had high pH. Regarding the nutrient concentrations (Table 2), the loamy sand soil had generally the lowest concentrations. The clay soil had highest concentration for most elements and peat soil stands in between. Rockdust, however, had lower concentrations of nutrients such as K, Cr, Cu, Mo and Zn compared to all three soils. Furthermore, rockdust had lower concentration of the potentially toxic non-nutrients Cd and Pb compared to the soils. Table 2 also shows the pseudo-total concentration of the elements in the different soil types after treatment with rockdust or quartz sand (soil samples taken at the end of growing season of year 3). Generally, in the case of elements which had higher concentration in rockdust than the soils, adding rockdust increased the pseudo-total concentration of the elements in soils, in particular Mg. Since the loamy sand soil was poor in most elements, the effect of rockdust in increasing the element concentrations was more obvious in this soil than in the clay and peat (Table 2).

Three years after the rockdust application, pH was significantly highest in the clay soil at 7.0, followed by the loamy sand at 6.8, and the peat at 6.4. Total C and

Table 2 Macro and microelement (pseudo)-total concentrations in original soils and rockdust, and in rockdust/quartz sand treated soil samples (ANOVA, n=4)

	Macroelements ($g kg^{-1}$ DW)						Microelements($mg kg^{-1}$ DW)										
	Ca	Fe	K	Mg	P	S	B	Cd	Co	Cr	Cu	Mn	Mo	Ni	Pb	Se	Zn
soils/rockdust																	
Clay	7.01	35.20	5.06	9.67	0.74	0.40	4.56	0.25	16.4	50.7	28.8	515	0.80	35.8	27.1	0.24	122
Peat	26.4	7.75	2.16	7.20	0.92	3.32	11.6	0.14	3.39	9.32	26.5	392	4.53	7.85	12.8	0.37	65.9
Loamy sand	3.25	11.70	0.90	3.51	0.78	0.16	<2	0.07	4.59	12.0	9.31	264	0.27	6.68	10.7	0.08	54.6
Rockdust	5.36	20.20	0.30	12.0	1.14	0.20	<2	0.01	12.4	5.61	8.17	297	<0.2	10.2	1.98	<0.02	48.5
ANOVA																	
Soil type	***	***	***	***	***	***	**	***	***	***	***	***	***	***	***	***	***
Clay	6.80^{b}	35.3^{a}	4.81^{a}	9.75^{a}	0.62^{b}	0.32^{b}	1.23^{ab}	0.21^{a}	13.3^{a}	46.9^{a}	26.3^{a}	460^{a}	0.73^{b}	31.2^{a}	23.2^{a}	0.15^{a}	102^{a}
Peat	15.6^{a}	6.41^{c}	0.56^{c}	3.78^{b}	0.61^{b}	1.42^{a}	1.69^{a}	0.11^{b}	2.33^{c}	5.90^{c}	12.6^{b}	191^{c}	1.60^{a}	5.27^{c}	7.77^{c}	0.13^{a}	46.9^{b}
Loamy sand	3.30^{c}	12.6^{b}	1.13^{b}	3.61^{b}	0.76^{a}	0.13^{c}	0.50^{b}	0.10^{b}	4.39^{b}	11.6^{b}	8.61^{c}	251^{b}	0.24^{c}	6.63^{b}	11.9^{b}	0.06^{b}	49.8^{b}
Treatment [a]	***	***	***	***	***	**	ns	***	***	**	***	***	***	ns	***	*	ns
HR	6.65^{A}	18.6^{A}	2.19^{A}	5.98^{A}	0.70^{A}	0.36^{A}	1.08	0.15^{A}	7.05^{A}	21.8^{A}	16.2^{A}	311^{A}	0.62^{AB}	14.3	14.3^{B}	0.10^{A}	69.2
LR	6.92^{A}	18.7^{A}	2.25^{A}	5.77^{A}	0.69^{A}	0.38^{A}	1.40	0.15^{A}	6.71^{A}	22.3^{A}	16.7^{A}	312^{A}	0.67^{A}	14.6	15.1^{A}	0.10^{A}	65.8
QS	6.00^{B}	16.7^{B}	2.05^{B}	5.40^{B}	0.61^{B}	0.33^{B}	0.94	0.13^{B}	6.21^{B}	20.4^{B}	14.7^{B}	280^{B}	0.56^{B}	14.2	13.4^{c}	0.09^{B}	63.9
Soil×Treatment	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Clay																	
HR	6.83	35.4	4.79	9.89	0.64	0.32	2.00	0.21	13.8	47.7	26.6	473	0.73	31.4	23.4	0.14	103
LR	7.03	36.4	4.97	10.0	0.64	0.33	2.27	0.21	13.3	48.1	26.9	465	0.75	31.9	23.8	0.15	105
QS	6.56	34.0	4.67	9.37	0.60	0.32	2.06	0.20	12.7	44.9	25.4	442	0.72	30.4	22.5	0.15	97.7
Peat																	
HR	15.6	7.66	0.62	4.25	0.67	1.41	2.49	0.12	2.88	5.71	12.9	203	1.58	4.86	7.67	0.12	52.9
LR	18.2	6.20	0.61	3.63	0.64	1.72	3.20	0.13	2.24	6.24	14.1	206	1.93	4.87	8.86	0.15	39.5
QS	13.5	5.36	0.44	3.46	0.52	1.19	2.03	0.09	1.86	5.76	10.9	165	1.37	6.09	6.78	0.12	48.4
Loamy sand																	
HR	3.45	12.8	1.16	3.79	0.80	0.14	<2	0.11	4.53	11.9	9.05	257	0.25	6.72	11.9	0.06	50.9
LR	3.41	13.5	1.17	3.69	0.79	0.14	<2	0.11	4.58	12.4	9.04	264	0.26	6.98	12.7	0.06	52.8
QS	3.05	11.6	1.05	3.36	0.70	0.12	<2	0.09	4.06	10.6	7.74	233	0.22	6.20	11.1	0.05	45.7

Significance: ns: not significant, * $p<0.05$, ** $p<0.001$, *** $p<0.001$. Different letters with the same pattern show significant difference as determined by ANOVA

[a] *HR* high application rate of rockdust; *LR* low application rate of rockdust; *QS* quartz sand

N (%) were highest in the peat soil followed by clay and loamy sand soils. Rockdust application did not make any significant change in the pH or C and N concentrations of the soils (data not shown). After rockdust application, as in the original soil, pseudo-total concentrations of most elements were highest in the clay soil (Table 2). Rockdust-treated soils generally had a significantly higher pseudo-total concentration of macro and microelements compared to the quartz sand treated soils, but there was no significant difference between high and low rate of rockdust application (Table 2). EDTA-extractable concentrations of all microelements were significantly different based on soil type while those of Cd, Ni and Pb were affected by rockdust application. The concentrations of Ni and Pb tended to be slightly lower, and that of Cd was significantly lower in the high rate compared to the low rate of rockdust application (Table 3).

Mineralogical studies

The mineralogical composition of the soils used in the experiment as well as the mineralogy of the rockdust applied to them is shown in Table 4. The rockdust was dominated by plagioclase feldspar, but also contained some K-feldspar, along with some pyroxene, and the iron and titanium oxides hematite and ilmenite. In addition some quartz was present along with a significant quantity of clay minerals, identified mainly as a variety of saponite. Considering the size of the box and the highest application rate of 5 $kg m^{-2}$, along with the bulk density of the soils, we calculated that this addition of rockdust would add 6 %, 2.7 % and 2.5 % by weight to the peat, clay and loamy sand soil, respectively. At these additions it was anticipated that it would only be possible to detect an alteration of the mineralogical composition using XRD in the peat soil, and this was indeed the case. This is illustrated in Fig. 1 which shows the detection of the enhanced content of clay minerals and of plagioclase feldspars in the high-rate rockdust amended peat compared to the low-rate amended peat. Other changes in mineralogy for any of the soils were calculated based on the mineralogical composition of the rockdust, bulk density *etc*. but none were substantial enough to be detected by XRD analysis. An example of this calculation for the peat soil before and after the addition of rockdust demonstrated the magnitude of the changes in mineralogical composition, which in the context of natural mineralogical variations such as those related to changes in soil parent material, are rather minor, even at the highest rate of application (Table 4).

Physiological response of microbial communities

Each of the 15 C sources produced detectable SIR in all soil samples (Fig. 2). The highest level of SIR was observed with α-keto glutaric acid and the lowest SIR for the base amino acids in the clay and loamy sand soils. The SIR rates were very different between the soil types with the highest SIR generally in the peat

Table 3 Microelement EDTA-extractable concentrations in soil samples (n=4)

Source of variation	Microelements ($mg kg^{-1}$ DW)								
	Cd	Co	Cr	Cu	Mn	Mo	Ni	Pb	Zn
Soil type	***	***	***	***	***	***	***	***	***
Clay	0.11^{a}	2.39^{a}	0.18^{a}	9.34^{a}	94.4^{b}	0.04^{b}	3.36^{a}	5.87^{a}	3.32^{b}
Peat	0.10^{a}	0.54^{b}	0.01^{c}	4.60^{b}	130^{a}	0.14^{a}	0.90^{b}	5.27^{b}	26.9^{a}
Loamy sand	0.07^{b}	0.49^{b}	0.06^{b}	2.74^{c}	42.0^{c}	0.01^{c}	0.43^{c}	4.17^{c}	2.45^{c}
Treatment[a]	*	ns	ns	ns	ns	ns	*	*	ns
HR	0.09^{B}	0.94	0.08	5.46	80.3	0.06	1.08^{AB}	5.04^{AB}	4.54
LR	0.10^{A}	0.99	0.07	5.72	83.8	0.05	1.13^{A}	5.35^{A}	4.51
QS	0.09^{B}	0.95	0.06	5.52	82.1	0.05	1.05^{B}	4.92^{B}	4.58

Significance: *ns* not significant, * $p<0.05$, ** $p<0.001$, *** $p<0.001$

Different letters with the same pattern show significant difference as determined by ANOVA

[a] *HR* high application rate of rockdust; *LR* low application rate of rockdust; *QS* quartz sand

Table 4 Mineralogical composition of soils, quartz sand and rockdust in percentage by weight as well as calculated alteration of mineralogy of the peat soil samples

	Quartz	Plagioclase	K-spar	Amphibole	Pyroxene	Hematite	Ilmenite	Dolomite	Clay Minerals [b]	Organic matter
Clay	21	17	12	3.1	–	–	–	–	44	3.6
Loamy sand	41	25	16	3.2	–	–	–	–	14	0.1
Peat	23	14	7.0	1.8	–	–	–	2.6	6.7	45
Quartz sand	98	–	1.9	–	–	–	–	–	–	–
Rockdust	6.7	60	7.5	–	6.6	1.5	3.2	–	15	–
Rockdust treated peat[a]	22	17	7.0	1.7	0.4	0.1	0.2	2.5	7.2	42

[a] Values were calculated based on the mineralogical composition of peat and rockdust (5 kgm^{-2}) by weight (in percentage)

[b] Clay minerals include illite, kaolinite, chlorite, and trioctahedral minerals

soil (Fig. 2). There was no significant difference in SIR for most C sources between clay and loamy sand soil samples. Irrespective of the soil type there was no significant difference between the different levels of rockdust/quartz sand treatments (Fig. 3). The multivariate analysis of the CLPPs obtained by SIR data showed that the greatest difference was between the soil types (P=0.0001), and was primarily on CV 1 which explained 74.63 % of the variation (Fig. 4). The variation among rockdust/quartz sand treatments within the peat and loamy sand soils were higher than clay soil, although there was no significant discrimination of the rockdust/quartz sand treatments overall (Fig. 4).

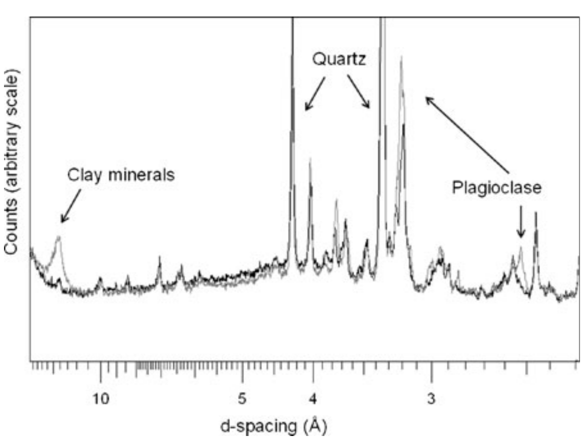

Fig. 1 XRD diagram of the enhanced content of clay minerals and plagioclase feldspars in the high-rate rockdust amended peat (*grey curves*) compared to the low-rate rockdust amended peat (*black curves*). Most peaks in the XRD patterns are due to plagioclase and/or quartz but are not labelled to aid clarity

Yield, element concentrations and off-take in wheat grains and forage crops

Grain yield was higher on the peat soil than on the clay and loamy sand soils, but did not differ between the treatments or cultivars (Table 5). The concentration and off-take of the macro and microelements in harvested wheat grains were generally significantly different based on the soil type and wheat cultivar, but no significant differences were observed between treatments (Tables 5 and 6). Between the two cultivars, Ölandsvete had higher concentrations of C, N, Mg, P and S and those of K and Na were higher in Triso (Table 5). Furthermore, Ölandsvete had higher concentration and off-take of Co, Fe, Mn, Mo, Ni and Zn than Triso. In case of Cd and Cu, the concentration was not significantly different between the two cultivars, while the off-take was significantly higher by Ölandsvete (Table 6).

Forage species, ryegrass and red clover, planted in the third growing season after rockdust application, grew well, and no sign of any element deficiency was observed. The peat soil produced the highest dry matter yield as sum of red clover and ryegrass (Fig. 5a). Dry matter yield for red clover and ryegrass individually was significantly different based on soil type but once again showed no relationship to rockdust application (Fig. 5b).

The concentrations of macro and microelements in ryegrass and red clover were generally significantly different based on soil types (Tables 7 and 8). Among all macro and microelements, rockdust application significantly increased the concentration of Na in both

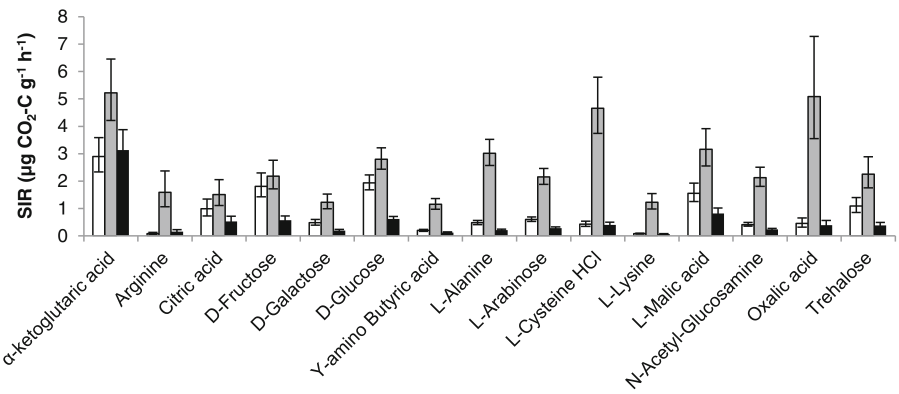

Fig. 2 Substrate-induced respiration for 15 C sources for clay (*white bars*), peat (*grey bars*) and loamy sand (black bars) soils based on the average values across the quartz sand/rockdust treatments. The error bars indicate 95 % confidence intervals

ryegrass and red clover at the high rate of application compared to the low rockdust rate and quartz sand treatments (Tables 7 and 8). The concentration of Ca in ryegrass was also affected significantly, however, with the highest concentration observed for quartz sand and rockdust low rate application (Table 7). The soil-by-rockdust interaction was significant only for Mg concentration, which was significantly lower in both ryegrass and red clover grown on clay soil with high rate of rockdust application (data not shown). Off-take of macro and microelements by forage species was generally significantly different between soil types and for Na significantly different between the rockdust/quartz sand treatments (Table 9).

Discussion

Effect of rockdust application on soil chemical, mineralogical and biological properties and element concentrations in soils

In general, soil amendments such as rockdust are assumed potentially to improve the nutrients status of soils by releasing nutrients and/or increasing the pH, particularly in acid soils. In our study, however, rockdust application did not induce any significant change of pH of the soils tested, despite the high original alkaline pH (9.1) of the rockdust and reasonably high rate of application. There are contrasting results in the literature on the effect of rockdust from different sources on pH. For example, Hinsinger *et al*. (1996) tested soil samples from 20 locations from Western Australia and found that pH increased in half of the soil samples after treating with finely ground granite powder. This increase, however, was very low (less than 0.3 pH units) despite a substantial rockdust application rate of 2 % by weight (compare to what we used in our current experiment with 2.5 % and 0.2 % as high and low rate of application, respectively). They, therefore, concluded, somewhat predictably, that the liming effect of granite powder is much lower than conventional liming materials such as crushed limestone with similar application rates. Barral Silva *et al*. (2005), however, stated that granite powder might function as an acid neutralizing material for acid soils in Glacia, Spain. Even though it was not as effective as common liming materials, it was still recommended for that specific region, but mainly because it could be obtained free of charge. The relatively high pH (Table 1) measured for the volcanic rockdust used in the current study can be explained simply as due to hydrolysis of the minerals present in it. For example, values for abrasion pH, a property which has long been used as a simple test to identify different minerals, vary between 8 and 10 (Stevens and Carron 1948) for plagioclase feldspars, which are the main minerals present in the rockdust according to analysis by XRD. The measured high pH does not imply a significant liming effect; in fact a negligible effect is predicted by direct measurement of the liming potential by titration (Table 1).

SEER rockdust originates from Collace quarry, Perthshire, where volcanic rocks from the Devonian Ochil Volcanic formation are quarried. The bulk chemical composition of the rockdust suggests an intermediate igneous rock composition (Campbell 2009), and the British Geological Survey (Cameron *et al*. 2010) list the quarried rock as a pyroxene-andesite. In addition to minerals that would be expected to occur in basic/intermediate volcanic rocks our mineralogical analysis indicated a significant

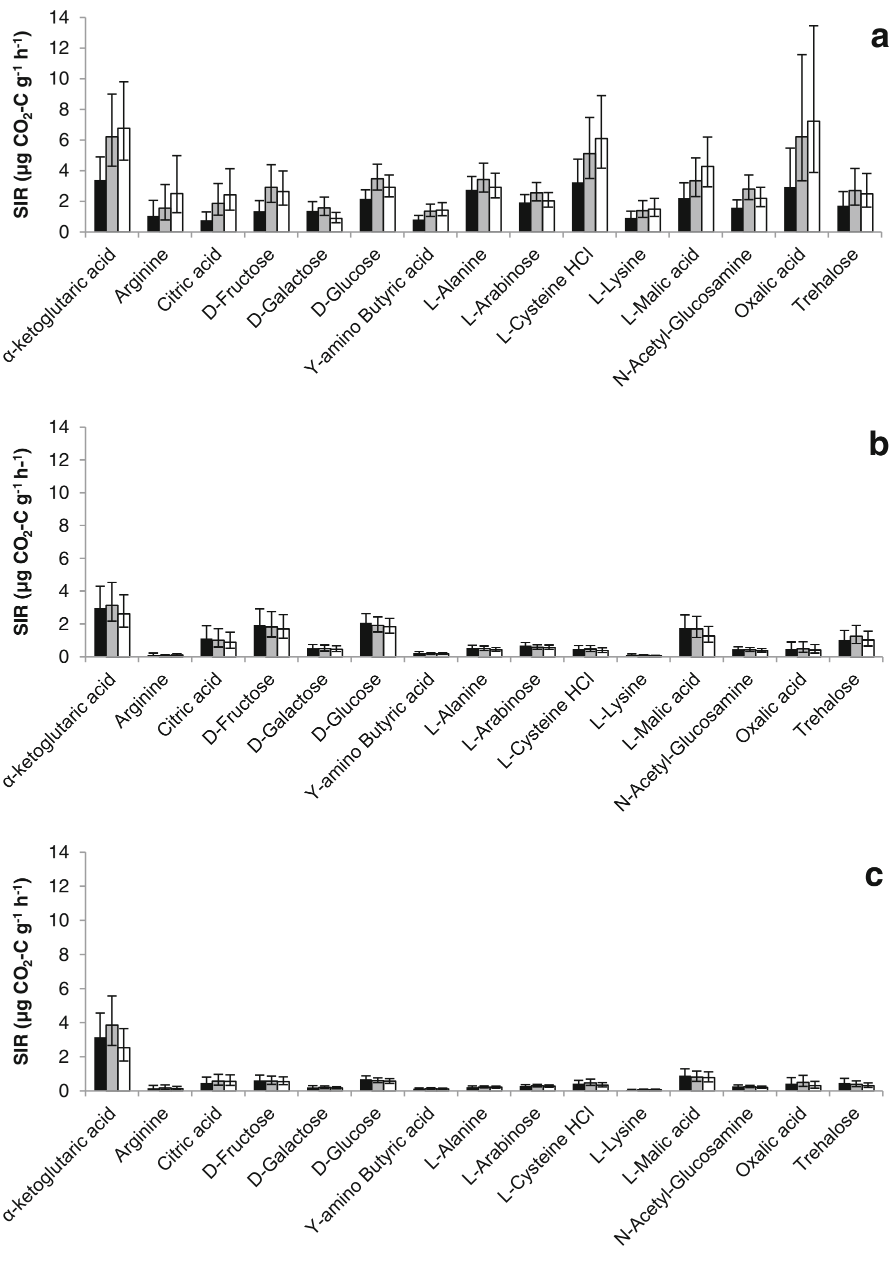

Fig. 3 Substrate-induced respiration for 15 C sources in peat soil (**a**), clay soil (**b**) and loamy sand soil (**c**) for high rate rockdust application (*black bars*), low rate rockdust application (*grey bars*) and quartz sand (*white bars*). The error bars indicate 95 % confidence intervals

quantity of clay minerals (≈ 15 %), identified as saponite. Clay minerals would not be expected to occur as primary minerals in igneous rocks and it is likely that the rockdust is actually derived, at least in part, from materials which have been altered, such as by weathering or hydrothermal solutions, rather than representing pristine igneous rock. Compared to acid igneous rocks, basic and intermediate igneous rocks such as basalts and andesites are known to generally contain higher concentrations of elements such as Cu, Zn, Cr, Co and Ni; which occur mainly in the easily weathered constituents (He *et al*. 2005; Kabata-Pendias 2001). As such, it could be argued that rocks of this type would be expected to represent the best case scenario for the potential supply of nutrients to soil when compared to other common rock types.

Chemical analysis of the rockdust showed that, in many cases, it had similar or lower concentrations of nutrients compared to particularly the clay soil (Table 2). Soils treated with high and low-rate of rockdust had significantly higher pseudo-total concentrations of

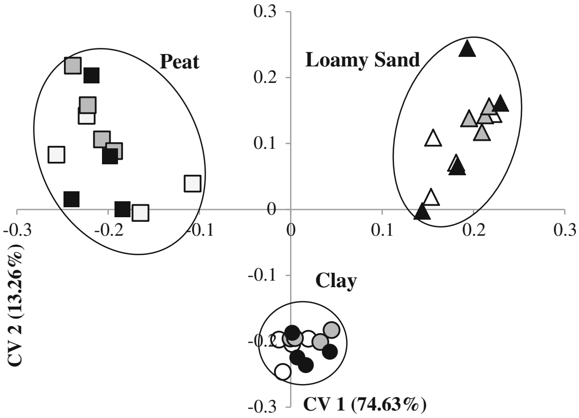

Fig. 4 Ordination diagram of first and second CVs for MicroResp CLPPs with 15 C sources. Triangles = loamy sand soil, squares = peat soil, circles = clay soil. Black = quartz sand, white =5 kg rockdust m^{-2} (HR), grey =0.5 kg rockdust m^{-2} (LR)

most macro and microelements (Table 2) than the quartz sand treated soils. The difference between the low and high rate of rockdust application, however, was not significant. Considering the concentration of elements in the soils before treating with rockdust/ quartz sand makes it obvious that in most cases, particularly in the clay and peat soil, both rockdust and quartz sand mainly diluted the elements of the soils, with quartz sand being the more effective diluting material than the rockdust. Therefore, the significant difference in many element concentrations between rockdust and quartz sand treated soils were not a "real addition". Rockdust, however, added nutrients such as Fe, Mg and P in the loamy sand soil (Table 2).

The EDTA-extractable element concentrations of the soils also confirmed the "dilution" rather than the "addition" effect of rockdust for some elements, where e.g. Cd and Pb concentrations were significantly higher in the low-rate rockdust application than high rate and quartz sand treatments (Table 3). Thus any concerns about increasing potential toxic elements in soils, by applying rockdust are negligible as these were also diluted as some of these elements were present in higher concentrations in the original soils than in the rockdust. Our results are in agreement with the results of Campbell (2009) who studied the effect of several types of rockdust from different origins. They also observed what they described as an "unexpected" decrease in the concentration of some elements by adding rockdust to the soil. Chaudhary *et al*. (2011) investigated the release of Cu, Zn, and Mn from a sulphide-rich rock powder in an incubation experiment. The rock powder had come from an old Cu mine with main minerals of chalcopyrite ($CuFeS_2$) and sphalerite (ZnS). Their results showed that the extractability and release of Cu was greatest, mainly due to the richness of the rock in Cu (19210 mgkg^{-1}); but it could not be considered as a supply of Zn and Mn. Hence, the initial concentration of the nutrients in the rockdust is an important factor in determining its effectiveness as a nutritious soil amendment.

The physiological profiles based on SIR of multiple C sources showed the soil types, despite having the same crops growing, had distinct microbial populations. Rockdust application itself however did not alter the SIR rate or physiological profiles of the microbial communities of these soils. We hypothesized that the addition of nutrients and new mineral surfaces for colonization might alter microbial responses but this was not found. Microbial responses to added C sources has previously shown to be a sensitive way of picking up soil treatments such as organic amendments and restoration practices (Chapman *et al*. 2007) suggesting rockdust has even in this part of the soil-plant system had a negligible effect. Applying rockdust to the soils even at the high rate added 6 % by weight to the peat soil and 2.7 and 2.5 % to the clay and loamy sand soils respectively. It seems that these addition rates did not make considerable changes to the mineralogy of the soils to significantly affect the microbial communities. Carson *et al*. (2007) reported that addition of mica, basalt and rock phosphate to soil microcosms induced substantial changes in both bacterial and fungal community composition. In their experiment, the original soil contained 99.8 % sand (>99 % quartz). Such a soil was more likely deficient in nutrients and adding mica, basalt and rock phosphate could have been considered as a more considerable change in terms of nutrients, leading to a change in microbial communities. However, this is perhaps not the case with agricultural soils, such as those we tested in our experiment. Aarnio *et al*. (2003) observed that apatite and biotite (used as slow-release fertilizers) increased the total content of Mg, K and P and the concentrations of exchangeable Mg and soluble P in soil and had a favorable effect on soil microbes still 10 years after application to a podzolic forest soil.

Table 5 Yield, macroelement concentrations and off-take in grains of two wheat cultivars (n=4)

Source of variation	Yield (gm^{-2})	Macroelements concentration (gkg^{-1} DW)								Macroelements off-take (gm^{-2})							
		C	N	Ca	K	Mg	Na	P	S	C	N	Ca	K	Mg	Na	P	S
Soil type	***	***	***	***	ns	***	***	***	***	***	***	***	***	***	**	***	***
Clay	117^{b}	416^{b}	18.4^{b}	0.53^{a}	5.71	1.43^{b}	0.026^{ab}	4.37^{b}	1.36^{b}	49^{b}	0.80^{b}	0.058^{b}	0.65^{b}	0.16^{b}	0.0029^{b}	0.48^{b}	0.15^{b}
Peat	206^{a}	421^{a}	29.6^{a}	0.40^{c}	5.59	1.71^{a}	0.022^{b}	5.03^{a}	1.90^{a}	87^{a}	2.08^{a}	0.078^{a}	1.09^{a}	0.33^{a}	0.0042^{a}	0.99^{a}	0.37^{a}
Loamy sand	110^{b}	415^{b}	17.2^{b}	0.46^{b}	5.47	1.35^{c}	0.029^{a}	4.14^{c}	1.23^{c}	46^{b}	0.70^{b}	0.048^{b}	0.58^{b}	0.14^{b}	0.0031^{b}	0.43^{b}	0.13^{b}
Treatment[a]	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
HR	146	418	21.7	0.45	5.60	1.49	0.025	4.49	1.48	61	1.05	0.061	0.78	0.21	0.0033	0.64	0.22
LR	136	417	22.9	0.48	5.57	1.52	0.027	4.59	1.56	57	1.05	0.061	0.73	0.20	0.0035	0.60	0.21
QS	152	416	20.5	0.45	5.60	1.48	0.025	4.46	1.45	63	1.12	0.063	0.81	0.22	0.0034	0.65	0.22
Wheat cultivar[b]	ns	*	***	ns	***	***	***	***	***	ns	ns	*	***	ns	***	ns	ns
ÖL	132	419^{A}	23.4^{A}	0.47	5.18^{B}	1.55^{A}	0.022^{B}	4.83^{A}	1.65^{A}	55	1.05	0.056^{B}	0.65^{B}	0.20	0.0027^{B}	0.62	0.22
TR	157	416^{B}	20.0^{B}	0.46	6.00^{A}	1.44^{B}	0.029^{A}	4.20^{B}	1.35^{B}	65	1.09	0.068^{A}	0.90^{A}	0.22	0.0041^{A}	0.64	0.21

Significance: *ns* not significant, * $p<0.05$, ** $p<0.01$, *** $p<0.001$

Different letters with the same pattern show significant difference as determined by ANOVA

[a] *HR* high application rate of rockdust; *LR* low application rate of rockdust; *QS* quartz sand

[b] *ÖL* cv. Ölandsvete, *TR* cv. Triso

Table 6 Microelement concentrations and off-take in grains of two wheat cultivars (n=4)

Source of variation	Microelements concentration (mg kg^{-1} DW)										Microelements off-take (mg m^{-2})									
	Cd	Co	Cr	Cu	Fe	Mn	Mo	Ni	Pb	Zn	Cd	Co	Cr	Cu	Fe	Mn	Mo	Ni	Pb	Zn
Soil type	***	***	ns	***	***	***	***	***	ns	***	***	***		***	***	***	ns	***		***
Clay	0.066^{a}	0.0034^{b}	<0.003	5.7^{a}	37^{b}	16^{c}	0.73^{a}	0.30^{a}	<0.001	33^{b}	0.0076^{a}	0.00038^{b}	n.a.	0.64^{a}	5.2^{b}	1.6^{b}	0.072	0.035^{a}	n.a.	3.4
Peat	0.024^{c}	0.0060^{a}	<0.003	4.0^{b}	59^{a}	129^{a}	0.47^{b}	0.02^{c}	<0.001	78^{a}	0.0050^{b}	0.00124^{a}	n.a.	0.77^{a}	15^{a}	20^{a}	0.068	0.011^{b}	n.a.	14
Loamy sand	0.039^{b}	0.0026^{c}	<0.003	3.9^{b}	30^{c}	24^{b}	0.63^{a}	0.04^{b}	<0.001	32^{b}	0.0043^{b}	0.00027^{b}	n.a.	0.42^{b}	4.1^{c}	2.2^{b}	0.058	0.007^{b}	n.a.	3.0
Treatment[a]	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns		ns	ns	ns	ns	ns		ns
HR	0.042	0.0038	<0.003	4.5	42	32	0.60	0.09	<0.001	40	0.0056	0.00060	n.a.	0.61	8.5	4.2	0.063	0.018	n.a.	5.3
LR	0.044	0.0041	<0.003	4.8	43	32	0.57	0.08	<0.001	42	0.0059	0.00065	n.a.	0.63	7.8	3.9	0.057	0.016	n.a.	5.3
QS	0.038	0.0039	<0.003	4.4	41	31	0.65	0.08	<0.001	39	0.0054	0.00065	n.a.	0.59	8.2	4.5	0.079	0.019	n.a.	5.9
Wheat cultivar[b]	ns	***	ns	ns	***	***	***	***	ns	***	**	ns		*	ns	ns	ns	***		ns
ÖL	0.040	0.0045^{A}	<0.003	4.6	47^{A}	34^{A}	0.70^{A}	0.13^{A}	<0.001	45^{A}	0.0048^{B}	0.00066	n.a.	0.55^{B}	8.2	4.0	0.069	0.022^{A}	n.a.	5.4
TR	0.042	0.0035^{B}	<0.003	4.5	38^{B}	30^{B}	0.52^{B}	0.05^{B}	<0.001	37^{B}	0.0065^{A}	0.00060	n.a.	0.67^{A}	8.1	4.4	0.063	0.013^{B}	n.a.	5.5

Significance: *ns* not significant, * $p<0.05$, ** $p<0.001$, *** $p<0.001$

Different letters with the same pattern show significant difference as determined by ANOVA

[a] *HR* high application rate of rockdust; *LR* low application rate of rockdust; *QS* quartz sand

[b] *ÖL* cv. Ölandsvete, *TR* cv. Triso

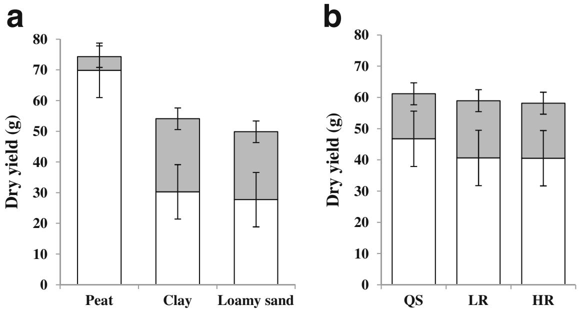

Fig. 5 Yield of red clover (*white bars*) and ryegrass (*grey bars*) produced on different soil types (**a**) and rockdust/quartz sand treatments (**b**). The error bars indicate 95 % confidence intervals

Effect of rockdust application on plant yield, element concentrations and off-take

In some of the studies investigating the effect of rockdust in providing nutrients for plants it has been concluded that slow release characteristics of rockdust may give it a significant advantage if release continues over a number of years (e.g. Sanz Scovino and Rowell 1988). In our study we had the opportunity to test the rockdust´s effect as a nutrient source both in the first and the third year after application. In the first year after application, rockdust did not improve wheat yield nor did it affect the concentration of any macro and microelements in the harvested wheat grains, despite the wide range of investigated elements. Bolland and Baker (2000) reported that granite dust when added 2 t ha^{-1} had no effect on grain yield of wheat in the year of application. Moreover, they stated that for "unknown reasons" the yield was reduced by 65 % by the application of 20 tha^{-1} granite dust compared to the negative control (no fertilizer, no dust) treatment. In a study by Jones *et al*. (2009) the addition of fine grained basaltic materials to compost and peat caused a significant 2-fold reduction in wheat biomass production and an overall reduction in most plant growth indicators in tomato plants in a pot experiment, harvested 2.5 months after application. However, Hinsinger *et al*. (1996) reported a significant increase in wheat biomass grown on poor soils treated with biotite-containing granite. They attributed this biomass increase to the K supply to the plants by granite dissolution, because of an observed significant increase in K content of the plant tissues. Wheat plants, however, did not respond to diorite application in their study. This difference between these two rock types

Table 7 Macro and microelement concentrations in ryegrass (n=4)

Source of variation	Macroelements (gkg^{-1} DW)								Microelements ($mgkg^{-1}$ DW)									
	C	N	Ca	K	Mg	Na	P	S	Cd	Co	Cr	Cu	Fe	Mn	Mo	Ni	Pb	Zn
Soil type	**	***	**	***	***	*	***	***	***	***	ns	**	***	***	***	***	ns	***
Clay	422^{b}	31.0^{b}	7.29^{b}	46.1^{b}	2.55^{b}	0.82^{a}	4.50^{c}	2.46^{b}	0.0162^{a}	0.19^{a}	0.27	8.04^{a}	263^{a}	39.6^{b}	11.5^{b}	2.07^{a}	0.03	21.5^{b}
Peat	427^{a}	41.9^{a}	7.42^{b}	57.5^{a}	3.20^{a}	0.40^{b}	5.36^{b}	3.04^{a}	0.0015^{b}	0.04^{c}	0.28	5.95^{b}	180^{b}	45.5^{b}	21.4^{a}	0.28^{c}	0.02	65.3^{a}
Loamy sand	423^{b}	29.9^{b}	8.16^{a}	45.8^{b}	2.70^{b}	0.45^{b}	6.19^{a}	2.21^{b}	0.0004^{b}	0.11^{b}	0.08	6.79^{ab}	229^{a}	58.0^{a}	3.77^{c}	0.51^{b}	0.02	21.0^{b}
Treatment[a]	ns	ns	*	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
HR	425	33.2	7.34^{B}	48.8	2.73	0.81^{A}	5.17	2.56	0.0014	0.10	0.21	6.45	229	49.5	8.70	0.71	0.01	33.7
LR	424	34.0	7.46^{AB}	49.9	2.81	0.43^{B}	5.42	2.58	0.0014	0.09	0.16	6.93	213	48.0	9.56	0.77	0.02	29.3
QS	424	36.1	8.07^{A}	50.7	2.91	0.43^{B}	5.46	2.57	0.0053	0.10	0.22	7.15	208	45.6	9.57	0.84	0.03	35.6

Significance: *ns* not significant, * $p<0.05$, ** $p<0.001$, *** $p<0.001$

Different letters with the same pattern show significant difference as determined by ANOVA

[a] *HR* high application rate of rockdust; *LR* low application rate of rockdust; *QS* quartz sand

Table 8 Macro and microelement concentrations in red clover (n=4)

Source of variation	Macroelements ($g kg^{-1}$ DW)								Microelements ($mg kg^{-1}$ DW)									
	C	N	Ca	K	Mg	Na	P	S	Cd	Co	Cr	Cu	Fe	Mn	Mo	Ni	Pb	Zn
Soil type	***	***	***	***	*	***	*	***	ns	***	ns	***	ns	***	***	***	ns	***
Clay	454^{a}	33.8^{b}	20.9^{b}	31.1^{b}	4.05^{ab}	0.092^{ab}	2.86^{b}	1.59^{b}	0.062	0.19^{a}	0.126	9.87^{a}	131	22.4^{b}	8.87^{b}	1.57^{a}	0.12	28.5^{b}
Peat	445^{b}	38.7^{a}	21.8^{b}	44.1^{a}	4.16^{a}	0.063^{b}	3.31^{a}	2.08^{a}	0.066	0.05^{b}	0.043	5.21^{c}	116	52.5^{a}	16.0^{a}	0.58^{b}	0.15	49.0^{a}
Loamy sand	453^{a}	32.6^{b}	24.2^{a}	27.1^{c}	3.75^{b}	0.142^{a}	3.19^{ab}	1.49^{b}	0.052	0.16^{a}	0.040	6.46^{b}	116	48.9^{a}	2.52^{c}	0.71^{b}	0.17	22.1^{c}
Treatment[a]	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
HR	450	33.3	22.1	34.2	3.81	0.128^{A}	2.99	1.66	0.059	0.12	0.050	6.51	120	43.4	6.99	0.87	0.22	33.0
LR	450	35.5	22.8	34.6	3.98	0.072^{B}	3.16	1.75	0.061	0.10	0.066	7.19	124	39.6	6.76	0.81	0.10	30.5
QS	452	36.3	22.0	33.5	4.17	0.086^{B}	3.22	1.75	0.060	0.11	0.094	6.81	118	40.9	7.59	0.92	0.13	28.9

Significance: *ns* not significant, * $p<0.05$, ** $p<0.001$, *** $p<0.001$

Different letters with the same pattern show significant difference as determined by ANOVA

[a] *HR* high application rate of rockdust; *LR* low application rate of rockdust; *QS* quartz sand

Table 9 Macro and microelements off-take of mixed stands of ryegrass and red clover (n=4)

Source of variation	Macroelements ($g m^{-2}$)								Microelements ($mg m^{-2}$)									
	C	N	Ca	K	Mg	Na	P	S	Cd	Co	Cr	Cu	Fe	Mn	Mo	Ni	Pb	Zn
Soil type	***	**	***	***	***	***	*	***	***	***	*	**	**	***	***	***	ns	***
Clay	120^{b}	6.28^{ab}	4.09^{b}	10.4^{b}	0.95^{b}	0.104^{a}	0.99^{b}	0.538^{b}	0.010^{b}	0.049^{a}	0.045^{a}	2.61^{a}	49.9^{a}	8.20^{c}	2.59^{b}	0.45^{a}	0.029	6.69^{b}
Peat	167^{a}	7.46^{a}	7.84^{a}	16.9^{a}	1.54^{a}	0.032^{b}	1.28^{a}	0.801^{a}	0.020^{a}	0.019^{c}	0.011^{b}	2.03^{ab}	37.2^{b}	19.5^{a}	6.01^{a}	0.20^{b}	0.063	18.6^{a}
Loamy sand	111^{b}	5.56^{b}	4.29^{b}	8.94^{b}	0.83^{b}	0.073^{a}	1.15^{ab}	0.459^{b}	0.006^{b}	0.033^{b}	0.009^{b}	1.69^{b}	37.9^{b}	13.3^{b}	0.77^{c}	0.15^{b}	0.040	5.48^{b}
Treatment[a]	ns	ns	ns	ns	ns	**	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
HR	129	6.25	5.19	12.1	1.06	0.086^{A}	1.11	0.582	0.010	0.030	0.017	1.90	40.0	14.1	1.98	0.22	0.050	8.72
LR	131	6.55	5.28	12.3	1.08	0.048^{B}	1.16	0.610	0.010	0.028	0.014	2.15	42.9	13.5	2.09	0.22	0.029	8.12
QS	137	6.51	5.75	11.8	1.20	0.049^{B}	1.16	0.606	0.013	0.033	0.023	2.28	40.3	13.4	2.32	0.28	0.053	8.87

Significance: *ns* not significant, * $p<0.05$, ** $p<0.001$, *** $p<0.001$

Different letters with the same pattern show significant difference as determined by ANOVA

[a] *HR* high application rate of rockdust; *LR* low application rate of rockdust; *QS* quartz

could be partly due to their mineralogical composition. However, on the other hand, it could be attributed to the “dilution effect” that rockdust might have had on compost and peat rich in nutrients in the study done by Jones *et al*. (2009), while Hinsinger *et al*. (1996) used a poor soil in their study.

In our current investigation, during the third growing season after application, rockdust did not affect the biomass yield of the forage species. Among all the elements tested in this study, only Na concentration in both species was increased by rockdust application, and then only at the high rate of application. This increase was most likely due to the abundance of Na in rockdust, probably hosted for the most part in plagioclase feldspar. Sodium is known to be taken up quite readily if available in the soil (Whitehead 2000) although it is thought not to be essential for most plants. The Ca concentration decreased in ryegrass by applying rockdust (Table 7). This may be, once again, explained by the dilution effect that rockdust have had on the element concentrations of the original soils. Apart from this, our findings are broadly in agreement with the results presented by Campbell (2009) which showed no significant effect of rockdust application on grass yield and quality in a field experiment. Jones *et al*. (2009) on the other hand found that rockdust addition to peat and green-waste compost significantly reduced growth of perennial ryegrass when adding green waste compost to minerals at a 30:70 (v/v) ratio.

In terms of adding potentially toxic elements, the rockdust which we used in our study is expected to be a low-hazard to the environment. Although it apparently failed to improve soil condition and plant growth in agricultural systems, there might still be other uses for it. In ecosystems with nutrient-poor soils dominated by plant species adapted to those conditions, addition of nutrients may constitute a major disturbance as it may lead a shift in species composition (Cale and Hobbs 1991; Trombulak and Frissell 2000). One possible way of introducing nutrients undesirably to the ecosystems is through road stabilizing materials. Mullerova *et al*. (2011) found that using either the slowly weathering amygdaloidal basaltic rock or granite as a stabilizer in road construction had significantly less effect on soil and vegetation than easily dissolving dolomite. The findings of our study, therefore, can be interesting in other fields of rockdust application, where the alteration in native plant communities as well as microbial communities of the soils and the surrounding environment is not only unfavorable but needs to be avoided. In such cases more investigations might be needed though to recommend this material as an environment-friendly stabilizing or the main material for road and walking trails construction in nature.

Conclusion

As indicated by our results, other than for Na uptake, the volcanic rockdust we used in this study did not alter the chemical properties or their measurable elemental (nutrients/potential toxics) content of three widely contrasting soils. It also failed to improve plant growth and quality in either high value (wheat) or low value (forage species) agricultural products grown in the first or the third year after application, respectively. The use of a sensitive microbial assay also showed it did not change the native microbial communities of the tested soil types.

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