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Rock Powder Can Improve Vermicompost Chemical Properties and Plant Nutrition: an On-farm Experiment

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ABSTRACT

Together with farmers, we evaluated nutrient availability from vermicomposted gneiss powder, assessed its influence on growth promotion, nutrition and heavy metal accumulation in maize plants and the effect on soil chemical properties in the field. Three soil treatments were applied: fertilization with vermicompost with gneiss powder, fertilization with vermicompost without gneiss powder, and soil without fertilization (control), in a randomized block design with five replicates. The dry weight of shoots and the concentrations of potassium, calcium, magnesium, manganese, nickel, chrome and lead in the dry matter of maize were higher with vermicompost with gneiss powder. In the soil, the potential of hydrogen and phosphorus, potassium and calcium concentrations were higher with vermicompost with gneiss. There were no detectable levels of heavy metal wastes in the soil after the experiment. We conclude that vermicomposted gneiss powder has potential for use in agriculture as a nutrient source and can improve soil chemical properties.

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Introduction

The high costs of soluble fertilizers and concerns about the environmental problems associated with their use and production trigger the use of wastes in agriculture as an alternative for chemical soil fertilization (Van Straaten 2007). Some organic and mineral wastes are not commercially exploited due to the lack of technical knowledge about their use or lack of availability of the product on the market. One of the alternatives is the use of rock powder because it can increase nutrients available to plants, nutritional reserves in the soil and plant resistance to biotic and abiotic stresses (Leonardos, Theodoro, and Assad 2000; Mancuso et al. 2014; Ramos et al. 2015; Silva et al. 2014). Here, we investigated the potential of gneiss rock powder to improve the quality of vermicompost for crop production.

Vermicompost is the result of transformation of organic wastes by earthworms. It is rich in organic matter and contributes to the restoration of physical and biological soil structures, acting as a natural fertilizer that neutralizes the soil pH and increases nutrient concentrations. It increases the resistance of plants against pests and diseases and can be used in any type of crop (Adhikary 2012). Vermicomposting is a low-cost process that generates a product with high nutritional value to plants (Singh et al. 2008). As such, it is a viable option for manuring soil (Lalander, Komakech, and Vinneras 2015). Rock powders are mining wastes that have potential to be used in agriculture

(Manning 2010). However, the release of nutrients from rock powder is slow, which, on the one hand can be beneficial as it provides a long-lasting residual effect, reducing losses by leaching and promoting long-term action of the applied input (Harley and Gilkes 2000; Leonardos, Theodoro, and Assad 2000; Van Straaten 2007). On the other hand, crops with short production cycles require rapid nutrients availability. It is possible to accelerate the solubility of minerals and the release of nutrients from the rock powder by associating them with simple management techniques such as vermicomposting (Leonardos, Theodoro, and Assad 2000; Souza et al. 2013). The addition of rock powder may thus further enhance the nutritional value of vermicompost without necessarily increasing production costs, because farmers can use regionally available wastes, in some cases from the farm itself. Through the process of vermicomposting, the solubility of rock powders can be increased through the effects of digestive enzymes (Carpenter et al. 2007) and through physical weathering (Suzuki, Matsubara, and Hoshino 2003) in the intestine of earthworms. Therefore, adding rock powder to organic waste that is composted by earthworms can increase the quality of the vermicompost (Souza et al. 2013). One concern, however, is that some rock powders contain heavy metals that can pollute the environment and cause health problem to plants and humans (Van Straaten 2007) and can therefore not be used as fertilizers. Moreover, these heavy metals may cause problems to the earthworms.

Although the number of studies on the technical and economic feasibility of the use of rock powder is on the rise, few papers have addressed the addition of rock powder to vermicompost (Adhami, Hosseini, and Owliaie 2014; Alvarez et al. 2004; Kumari and Ushakumari 2002; Souza et al. 2013) and, to our knowledge, none of these are based on farm studies or with participation of farmers. For example, Escosteguy and Klamt (1998) reported small increases in the levels of nutrients available in the soil by adding basalt powder. Arbiato (2005) observed that granite powder supplied 40% of the plant's potassium (K) requirements and phonolite and phlogopite powders were able to meet 66% of the K requirements of lettuce. Carvalho (2012) reported increased growth of common bean plants and improvement of soil characteristics resulting from added gneiss powder in a field study. In the current study, we used a participatory on-farm experiment to evaluate the effects of adding gneiss rock powder to vermicompost on the growth of maize plants, as well as on chemical properties of the plants and the soil.

Gneiss is a widely distributed type of metamorphic rock. It is composed of different minerals, predominantly K-feldspar, quartz, mica (biotite), and amphiboles. Gneiss is rich in nutrients such as silicon, potassium, calcium, iron, and zinc. Therefore, powder of this rock is an alternative K source, and can be used to reduce the dependence on commercial inputs of this nutrient.

Based on the yearly production of ornamental stone in Brazil (10.5 million tons) and the estimated losses, the total production of wastes in quarries and sawmills amounts to c. 3 million tons per year, hence, it is amply available for agricultural use. These wastes often cause environmental problems. This is especially the situation with wastes generated in sawmills (wastewater from rock sawmills), which primarily consist of fine rock powder, and which can contaminate rivers, cause visual pollution and lung diseases (Mechi and Sanches 2010). Hence, use of these wastes helps resolve these pollution problems.

Currently, Brazil imports 92% of its potassium and 53% of the phosphate used in agriculture (IBRAM 2012), suggesting that the sustainability of Brazilian agriculture is vulnerable because of its high dependence on imported fertilizers (Gliessman 2015; Pretty 2008). Thus, alternatives to chemical fertilizers must be sought in order to raise agricultural sustainability without losing productivity. The use of rock powder as a fertilizer has the potential to reduce the dependence on the imported inorganic fertilizers (Theodoro et al. 2006). Despite this, rock powder has only recently been considered as a potential fertilizer in Brazil (Brazil 2013).

The farmers in our study region acknowledged the advantages of using vermicompost over using compost; however, its use is not common among farmers (Souza et al. 2015). Many farmers either believe that wormeries require expensive infrastructure (Schiedeck et al. 2007) or they do not have access to the most productive earthworm species (Souza et al. 2015). We therefore carried out research on-farm to

evaluate the feasibility of this method under farming conditions, using it a learning process for both researchers and farmers. Too many technologies and practices have been proven productive and environmentally feasible on research stations, but have hardly been used by farmers (Pretty 1995). We therefore believe that the worldwide challenges that are facing agriculture can only be addressed efficiently using participatory approaches involving farmers and researchers, as participation is an essential component of any learning process. The objectives of our field study were to evaluate the availability of nutrients in gneiss powder after being vermicomposted, assess the effect of vermicompost enriched with rock powder on maize growth and nutritional status, the heavy metal accumulation in maize, and the influence of the vermicomposted rock powder on soil chemical characteristics. Earlier research under greenhouse conditions demonstrated that gneiss powder increased the growth of maize and did not negatively affect the growth of earthworms. It also improved the chemical quality of the vermicompost and plant growth, and did not result in high levels of heavy metals in the plants and soil (Souza 2014; Souza et al. 2013).

Material and methods

The experiment was conducted on a farm located in Divino, in the Zona da Mata, Minas Gerais, Brazil (20° 36' S and 42° 08' W). The landscape is characterized by an undulating relief with few plains, a mean altitude of 950 m above sea level and a mean annual temperature of 20.4°C. The natural soil fertility is mostly low, and family farming is the predominant land use. The farmers who participated in the research were enrolled in the peasant-to-peasant events organized by the local farmers organization, the Alternative Centre of Technology (CTA, a non-governmental organization), and the Federal University of Viçosa, as part of the agroecological activities that have been developed in the region since 1993 (Cardoso et al. 2001).

To produce the vermicompost, four wormeries (approximately 0.80 m wide x 1.20 m long x 0.30 m high) were built together with 14 farmers, at the farm where the experiment was conducted. The participating farmers were offered earthworms to start their own wormeries. The construction of the wormeries followed Schiedeck et al. (2007), using simple materials such as bamboo and plastic. We used cattle manure produced on the farm and the worm species *Eisenia andrei* (the red earthworm) to produce vermicompost.

Preparation and characterization of gneiss powder

Gneiss powder was obtained from quarries in the region and contained compounds such as quartz, k-feldspar, plagioclase, amphibole, biotite, rutile, and apatite (Carvalho 2012). The gneiss powder was air-dried and sieved (< 0.212 mm and > 0.106 mm). See Table 1 for chemical characterization.

Preparation of vermicompost

To prepare vermicompost, the manure was crumbled and mixed to obtain homogeneity in moisture and particle size. A sample of this crumbled manure was used for chemical characterization (Table 2).

Table 1. Chemical characterization of gneiss powder.

Macroelements ¹							
SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	P ₂ O ₅	MnO
54.7	14.8	12.3	6.1	2.4	2.5	1.1	0.2
Microelements ²							
		Cu	Zn	Ni	Cd	Cr	Pb
		11	148	4.4	2.3	14.3	9.8

Gneiss powder was stored in paper bags and dried in a forced air oven (65°C) for 72 h. ¹ Macroelements were analyzed with X-ray fluorescence spectrometry, given in % (w/w); ² Microelements were analyzed with atomic absorption spectrophotometry after nitro-perchloric digestion and are given in mg kg⁻¹.

Table 2. Chemical characterization of bovine manure.

pH	C/N ⁽¹⁾	N ⁽²⁾	P ⁽²⁾	K ⁽²⁾	S ⁽²⁾	Ca ⁽²⁾	Mg ⁽²⁾	Mn ⁽³⁾	Cu ⁽³⁾	Zn ⁽³⁾	Ni ⁽³⁾	Cd ⁽³⁾	Cr ⁽³⁾	Pb ⁽³⁾
7.6	16	11	8	20	2.5	8	3.5	162	17	86	9.5	0.4	21.6	10

A sample of this material was weighed, ground, and was digested in a nitro-perchloric acid mixture and quantified with atomic absorption spectrophotometry (Silva 2009). ⁽¹⁾Ratio of Carbon to Nitrogen; ⁽²⁾ in g kg⁻¹; ⁽³⁾ in mg kg⁻¹

Eisenia andrei was pre-incubated in cattle manure one week before the experiment to eliminate any remains of previous food of the earthworms. The worms were placed at the bottom of the wormery and covered with cattle manure. Per 100 kg, 1 L of worms (approximately 1200 worms) was added. Gneiss powder was added to the manure of two of the four wormeries at a rate of 20% (w/w).

After 90 days, the vermicomposts were dried, ground and chemically analyzed (Table 3). The maximum permitted concentrations, according to regulations from Brazil, the European Commission and the United States of America, of heavy metal in organic fertilizers, soil and plants are listed in Table 4.

Growth evaluation and chemical analyses of maize plants

The experiment was carried out in an Oxisol (Table 5 for chemical characterization of the soil). The experimental area was traditionally used for maize production, with liming every two years and annual soil fertilization with an NPK fertilizer, consisting of a mixture of nitrogen (N), phosphorus (P), potassium (K) (4:14:8) and ammonium sulfate. The experiment consisted of a randomized block design with three treatments and five replicates. Each replicate was a 3.0 x 2.7 m plot, consisting of three rows of maize (variety Asteca), managed according to the practice of the family (no pesticides, manual weeding, no ploughing). Maize was hand-planted by the farmer families and the researchers, in rows spaced 0.90 cm apart and five plants/meter. The treatments consisted of adding vermicompost, vermicompost with gneiss powder and a control treatment without vermicompost.

Table 3. Chemical properties of the vermicomposts at the end of the vermicomposting. process.

	P ⁽¹⁾	K ⁽¹⁾	Ca ⁽¹⁾	Mg ⁽¹⁾	Fe ⁽²⁾	Mn ⁽²⁾
Compost ⁽³⁾	7.3	23.2	12.3	2.6	373.0	91.3
Compost with gneiss ⁽⁴⁾	7.7	35.4	19.6	3.8	389.0	106.2
	Cu ⁽²⁾	Zn ⁽²⁾	Ni ⁽²⁾	Cd ⁽²⁾	Cr ⁽²⁾	Pb ⁽²⁾
Compost ⁽³⁾	15.9	63.6	4.3	ud ⁽⁵⁾	4.5	5.9
Compost with gneiss ⁽⁴⁾	27.3	71.3	7.8	ud	16.9	7.7

The vermicomposts were chemically analyzed to determine the levels of P, K, Ca, Mg, Mn, Fe, Cu, Zn, Ni, Cd, Cr and Pb after nitro-perchloric digestion (Silva 2009). The P contents were determined colorimetrically; K contents were determined by flame emission photometry; the Ca, Mg, Mn, Fe, Cu, Zn, Ni, Cd, Cr contents were determined by atomic absorption spectrophotometry (Silva 2009). ⁽¹⁾in g kg⁻¹; ⁽²⁾ in mg kg⁻¹; ⁽³⁾Vermicomposted bovine manure without rock powder; ⁽⁴⁾ Vermicomposted bovine manure with 20% gneiss powder. ⁽⁵⁾Undetected: concentrations below the detectable limit of the method.

Table 4. Maximum concentrations (mg/kg) of heavy metals allowed in organic fertilizers, soil and plants in Brazil, the EU and the USA.

		Cu	Zn	Ni	Cd	Cr	Pb
Organic fertilizer	Brazil ⁽¹⁾	no limit ⁽⁵⁾	no limit	70	3	200	150
	EU ⁽²⁾	33–60	109–347	4–44	0.2–0.7	5–56	5–18
	USA ⁽³⁾	2–172	15–556	SL	0.1–0.8	1.1–55	1.1–27
Soil	Brazil ⁽¹⁾	49	46.5	21.5	<0.4	75	19.5
	EU ⁽³⁾	50–140	150–300	20–75	1–3	100–150	50–300
	USA ⁽³⁾	60–125	400–700	100	3–8	75–400	100–400
Plant	Brazil ⁽¹⁾	30	50	5	0.5	0.1	0.5
	EU ⁽²⁾	no limit	no limit	no limit	0.2	no limit	0.3
	USA ⁽⁴⁾	5–20	10–50	1–10	0.05–0.5	2	0.5–10

⁽¹⁾ MAPA (2006), COPAM (2011), Anvisa (1965, 1998); ⁽²⁾ European Commission (2006); ⁽³⁾ Alloway (1995); ⁽⁴⁾ Kabata-Pendias (2010);

⁽⁵⁾ No threshold established by the normative regulation.

Table 5. Chemical properties of the Oxisol of a family farm in Divino, Minas Gerais, Brazil.

P ⁽¹⁾	K ⁽¹⁾	Ca ⁺²⁽²⁾	Mg ^{+2 (2)}	Al ^{+3 (2)}	SB ⁽²⁾	CEC ⁽²⁾	V ^{(3)l}	M ⁽³⁾
2.2	93.0	3.6	1.4	0.0	5.2	7.5	69	0.0
pH	OM ⁽⁴⁾	P-rem ⁽⁵⁾	Zn ⁽⁶⁾	Cu ⁽⁶⁾	Cr ⁽⁶⁾	Ni ⁽⁶⁾	Cd ⁽⁶⁾	Pb ⁽⁶⁾
6.2	3.1	28.6	1.2	0.3	0.0	0.0	0.0	0.0

P content of the soil was determined colorimetrically, K by flame emission photometry and the other elements by atomic absorption spectrophotometry (Silva 2009). SB: Sum of basic cations (Ca, Mg and K); CEC: Potential cation exchange capacity at pH 7.0; V: Percentage of CEC at pH7.0 occupied by basic cations; M: Percentage of effective CEC occupied by Al³⁺; P-rem: Remaining phosphorus in solution after stirring 7.5 g soil into 75 mL of a solution of 60 mg L⁻¹ of P. ⁽¹⁾ in mg dm⁻³; ⁽²⁾ in cmol_c dm⁻³; ⁽³⁾ in %; ⁽⁴⁾ in dag kg⁻¹; ⁽⁵⁾ Organic Matter in mg L⁻¹; ⁽⁶⁾ in mg kg⁻¹;

Vermicomposts were applied at a rate corresponding to 20 t ha⁻¹ of dry material. No additional fertilizer was applied before or during cultivation.

Sixty-five days after planting, six plants per sampling unit were cut to assess plant growth and nutrition. The farmer's family participated in the qualitative evaluation and harvesting of the plants. The plants were washed with water plus detergent (1 mL L⁻¹), subsequently with tap water and finally with distilled water. The plant material was packed in paper bags and dried in a forced air oven at 65°C for 72 h. Once dry, all material was weighed, ground and packed in polyethylene bags and stored until analysis. The shoot samples were digested in a nitro-perchloric acid mixture (Silva 2009) and the P, K, calcium Ca), magnesium (Mg), manganese (Mn), iron (Fe), copper (Cu), zinc (Zn), nickel (Ni), cadmium (Cd), chrome (Cr) and lead (Pb) concentrations were determined by atomic absorption spectrophotometry (Silva 2009).

Assessment of soil changes

To evaluate changes in the soil chemical properties, 15 single samples were collected in the 0–20 cm soil layer near the maize rows in each experimental unit. These single samples were combined into one sample per experimental unit, resulting in 5 of such combined samples per treatment. The samples were air-dried and sieved (<2 mm). The potential of hydrogen (pH), and the concentrations of P, K, Ca, Mg, Fe, Mn, Cu, Zn, Ni, Cd, Cr, and Pb in the soil after maize cultivation were determined using Mehlich-1 to determine P, K, micronutrients and metals and 1 mol L⁻¹ extractor potassium chloride (KCl) for extraction of Ca and Mg (Silva 2009).

Statistical analyses

Because we measured several response variables from the same replicates, we first performed MANOVAs for the concentrations of nutrients and heavy metals found in the plant shoots and in the soil at the end of the experiment. All these MANOVAs showed a significant effect of treatments on the concentrations. Therefore, the nutrients and heavy metals in the shoots were subsequently analysed separately with linear mixed effects models (lme of the package NLME of R, Pinheiro et al. 2014, R Development Core Team 2015) with treatment as fixed factor and block as random factor. Plant weights and soil samples were not replicated per block and were therefore analysed with generalized linear models (glm of R) with a Gaussian or gamma error distribution, depending on the distribution of the residuals. Contrasts among treatments were assessed with the glht function (package lsmeans of R, Lenth 2016).

Results

Dry biomass of maize shoots

The mean dry shoot biomass of maize, 65 days after planting, differed significantly among treatments ($F_{2,12} = 4.64$, $p = 0.032$), and was significantly higher in the vermicompost plus gneiss treatment than in the control (Figure 1). Plants with vermicompost with gneiss produced 21%

Figure 1. Dry matter of maize shoots ($n = 5$) 65 days after planting in a treatment without added compost (Control), a treatment with added vermicompost and a treatment with vermicompost plus 20% gneiss powder (Vermicompost + gneiss) or no rock powder (Vermicompost) and control. Error bars with different letters differ significantly. Bars represent standard errors.

more biomass than plants with simple vermicompost. This increased growth was also observed by the farmer.

Chemical analysis of plants

Overall, there was a significant effect of treatment on the concentrations of nutrients in the maize shoots (MANOVA, Pillai-Bartlett statistic = 1.95, d.f. = 2, $p < 0.0001$). The concentrations of P in the maize shoots differed significantly among treatments ($\text{Chi}^2 = 14.1$, d.f. = 2, $p < 0.001$), and was significantly higher in the vermicompost treatment than in the other treatments (Table 6). The concentrations of K ($\text{Chi}^2 = 60.7$, d.f. = 2, $p < 0.0001$) and of Fe ($\text{Chi}^2 = 157.9$, d.f. = 2, $p = 0.0001$) differed significantly among treatments, and were highest in maize fertilized with vermicompost with gneiss powder, lower in plants fertilized with vermicompost without gneiss and lowest in the control (Table 6). The concentrations of Ca ($\text{Chi}^2 = 57.4$, d.f. = 2, $p < 0.0001$), Mg ($\text{Chi}^2 = 115.0$, d.f. = 2, $p < 0.0001$) and Mn ($\text{Chi}^2 = 103.3$, d.f. = 2, $p < 0.0001$) also differed significantly among treatments, and were higher in treatments fertilized with vermicompost with gneiss powder than in the other two treatments, which did not differ significantly (Table 6).

Overall, there was a significant effect of compost type on the heavy metal concentrations in the shoots (MANOVA, Pillai-Bartlett statistic = 1.79, d.f. = 2, $p < 0.0001$). The concentrations of Cu in the maize shoots varied significantly with treatment ($\text{Chi}^2 = 23.2$, d.f. = 2, $p < 0.0001$), and were significantly higher in the two treatments with vermicompost than in the control (Table 7). The concentration of Zn differed significantly between treatments ($\text{Chi}^2 = 47.1$, d.f. = 2, $p < 0.0001$), and was higher in treatments fertilized with vermicompost with gneiss powder than in the other two treatments (Table 7). Ni, Cd, Cr and Pb were not detected in the shoots of plants in the control that received no vermicompost (Table 2). The concentrations of Ni ($\text{Chi}^2 = 173.5$; $p < 0.0001$), Cr ($\text{Chi}^2 =$

Table 6. Concentrations of P, K, Ca, Mg, Fe, and Mn in the dry matter of maize shoots fertilized with vermicompost with 20% gneiss powder or no rock powder and control (no fertilization).

	P ⁽¹⁾	K ⁽¹⁾	Ca ⁽¹⁾	Mg ⁽¹⁾	Fe ⁽²⁾	Mn ⁽²⁾
Compost	1.82 (0.01) ^a	13.8 (0.04) ^c	2.35(0.04) ^b	1.65 (0.002) ^b	179.0 (1.67) ^b	35.36 (1.43) ^b
Gneiss-compost	1.68 (0.01) ^b	15.5 (0.02) ^a	2.86 (0.04) ^a	2.31 (0.010) ^a	185.9 (3.02) ^a	44.16 (1.83) ^a
Control	1.72 (0.01) ^b	14.6 (0.02) ^b	2.51 (0.09) ^b	1.84 (0.002) ^b	147.7 (2.05) ^c	33.78 (0.62) ^b

Averages ($n = 5$, standard error) within each column followed by the same letter do not differ significantly (Contrasts after a linear mixed effects model, $p < 0.05$). ¹ In g kg⁻¹ dry matter; ² in mg kg⁻¹ dry matter.

Table 7. Concentrations of the heavy metals Cu, Zn, Ni, Cd, Cr and Pb (mg kg⁻¹) in the shoot dry matter of maize fertilized with vermicompost with 20% gneiss powder or vermicompost only and in the control (unfertilized soil).

	Cu	Zn	Ni	Cd	Cr	Pb
Compost	4.9 (0.43) ^a	23.0 (0.63) ^b	4.0 (0.05) ^b	ud ¹	0.9 (0.02) ^b	3.7 (0.09) ^b
Gneiss-compost	5.1 (0.23) ^a	29.9 (3.10) ^a	6.4 (0.05) ^a	ud	6.1 (0.09) ^a	5.6 (0.13) ^a
Control	3.9 (0.28) ^b	22.6 (1.36) ^b	ud	ud	ud	ud

Averages (n = 5, standard error) within each column followed by the same letter do not differ significantly (Contrasts after a linear mixed effects model, $p < 0.05$). ¹Undetected: concentrations below the detectable limit of the method.

280.3; $p < 0.0001$) and Pb ($\text{Chi}^2 = 119.8$; $p < 0.0001$) were higher in maize fertilized with vermicompost with gneiss powder than with vermicompost (Table 7). These values exceeded the threshold set by the Brazilian legislation for cereals and vegetables and maximum limits suggested by Kabata-Pendias (2010) for the USA (Table 4).

Soil characteristics after cultivation

Overall, there was a significant effect of vermicompost type on the concentrations of nutrients in the soil after cultivation (Table 8, MANOVA, Pillai-Bartlett statistic = 1.77, d.f. = 2, $p = 0.0018$). The concentrations of P ($F_{2,12} = 149.9$, $p < 0.0001$), Ca ($F_{2,12} = 6.84$, $p = 0.010$), Mg ($F_{2,12} = 9.25$, $p = 0.0037$) and Mn ($F_{2,12} = 4.91$, $p = 0.028$) in the soil after maize cultivation were significantly affected by treatment, as were the soil pH ($F_{2,12} = 11.03$, $p = 0.0019$) and the amount of organic matter ($F_{2,12} = 11.4$, $p = 0.0017$). After cultivation, the P concentration in the soil with gneiss-enriched vermicompost was almost fourfold higher than in the control (Table 8) and before the experiment (Table 5), and almost twofold higher than in the soil that received non-enriched vermicompost (Table 8). The concentrations of Ca and Mn in soils with vermicompost was significantly higher than in the control treatment, with the concentrations in the treatment with enriched vermicompost being non-significantly higher than in the treatment with non-enriched vermicompost (Table 8). Concentrations of Mg were higher in the soils that received vermicompost than in the control (Table 8). As expected, soil organic matter was increased in the soils that received vermicompost compared to the control (Table 8). The pH increased significantly in the soil treatment with gneiss powder compared to the other treatments ($F_{2,12} = 11.03$, $p = 0.0019$). There were no significant differences in the concentrations of K ($F_{2,12} = 1.63$, $p = 0.24$) and Fe ($F_{2,12} = 0.67$, $p = 0.53$) after cultivation (Table 8).

After maize cultivation, the soil concentrations of heavy metals differed significantly among treatments (MANOVA, Pillai-Bartlett statistic = 1.44, d.f. = 2, $p = 0.018$). Control soils did not contain detectable concentrations of Ni, Cr and Pb; the concentrations of these elements were similar in both treatments with vermicompost (Table 9). Cu concentrations differed significantly among treatments ($\text{Chi}^2 = 11.6$, d.f. = 2, $p = 0.0031$) and were higher in soil that had received enriched vermicompost than in the other two treatments (Table 4). The concentrations of Zn also varied significantly among treatments ($\text{Chi}^2 = 14.4$, d.f. = 2, $p < 0.001$), and was higher in the two

Table 8. Chemical properties of the soil after cultivation of maize fertilized with vermicompost with 20% gneiss powder or vermicompost only and control (unfertilized soil).

	P ¹	K ¹	Ca ²⁺ (2)	Mg ²⁺ (2)
Compost	5.6 (0.35) ^b	117.8 (12.69) ^b	3.3 (0.12) ^b	1.5 (0.03) ^a
Gneiss-compost	10.6 (0.61) ^a	138.0 (14.55) ^a	3.6 (0.11) ^a	1.4 (0.05) ^a
Control	2.8 (0.09) ^c	97.6 (17.55) ^c	3.0 (0.09) ^c	1.2 (0.04) ^b
	pH	OM (3)	Mn (1)	Fe (1)
Compost	6.3 (0.08) ^b	4.4 (0.15) ^a	59.3 (3.92) ^a	51.8 (5.43) ^a
Gneiss-compost	6.7 (0.07) ^a	4.1 (0.10) ^a	66.0 (2.86) ^b	55.6 (4.28) ^a
Control	6.3 (0.04) ^b	3.4 (0.10) ^b	51.8 (2.72) ^a	59.8 (4.85) ^a

Per column, means (n = 5, standard error) followed by the same letter do not differ significantly (contrasts after generalized linear model). ⁽¹⁾ in mg kg⁻¹; ⁽²⁾ in cmol_c dm⁻³ and ⁽³⁾ in dag kg⁻¹;

Table 9. Mean concentrations of the heavy metals Cu, Zn, Ni, Cd, Cr and Pb (mg kg^{-1}) in the soil after cultivation of maize fertilized with vermicompost (Compost), with vermicompost with 20% gneiss powder (Gneiss-compost), and unfertilized soil (Control).

	Cu	Zn	Ni	Cd	Cr	Pb
Compost	0.30 (0.06) ^a	2.98 (0.17) ^b	0.162 (0.024) ^a	0.222 (0.020) ^a	0.382 (0.020) ^a	0.30 (0.06) ^a
Gneiss-compost	0.52 (0.04) ^b	3.04 (0.34) ^b	0.244 (0.023) ^b	0.221 (0.038) ^a	0.401 (0.032) ^a	0.52 (0.04) ^b
Control	0.34 (0.02) ^a	1.50 (0.30) ^a	Ud ⁽¹⁾	Ud	Ud	0.34 (0.02) ^a

Given are means ($n = 5$, standard error). Within each column, means followed by the same letter do not differ significantly (Contrasts after a linear mixed effects model ($p < 0.05$)). ¹ Undetected: concentrations below the detectable limit of the method.

vermicompost treatments than in the control. No cadmium was detected in the soil after cultivation. In all treatments (Table 9), the metal concentrations were below the reference values for soil quality, defined by regulations of the state of Minas Gerais, Brazil, (Copam, 2011), and maximum limits suggested by Alloway (1995) for USA and the European Commission (2006) (Table 4).

Discussion

Dry shoot biomass of maize

The similar growth of the maize plants from the control treatment and the plants cultivated in the vermicompost (Figure 1), can be attributed to the wild maize variety (Asteca) being adapted to the local circumstances and the good soil conditions (Table 5), because of the history of chemical fertilization of the soil. Plants that were supplied with gneiss-enriched vermicompost grew significantly better than plants without vermicompost, and this can be attributed to the higher availability of nutrients from the rock powder (Carvalho 2012). Similar results were reported by Souza et al. (2013), where gneiss powder added to vermicomposting substrate stimulated maize growth in a controlled environment. Thus, the higher dry matter production of field-grown plants with gneiss-enriched vermicompost indicates the possibility of using rock powder with vermicompost for soil fertilization.

Evaluation of plant nutrition

The high K, Ca, Mg, and Mn concentrations in the shoot dry matter of maize grown in soil with gneiss-enriched vermicompost (Table 6) shows that the process of vermicomposting contributed to providing these elements. Several papers have reported such increased growth of plants after the supply of rock powder (Carvalho 2012; Harley and Gilkes 2000; Martins et al. 2008; Souza et al. 2013; Wang et al. 2000).

Adding gneiss powder to the vermicomposting substrate not only increased the plant nutrients, but also the concentrations of the heavy metals Ni, Cr and Pb (Table 7). Among these, nickel is the only element recently identified as essential for higher plants (Brown, Welch, and Cary 1987). However, the higher shoot concentrations of Ni, Cr and Pb in the treatment with gneiss powder cannot be ascribed to the concentrations of these elements in the rock alone, but to the manure as well (Table 2). Heavy metal concentrations in the manure were higher than those in the gneiss powder used here, but were within the maximum permissible levels of metals allowed in organic fertilizers (Table 4). The presence of heavy metals in manure depends on the origin of the material and is related to the animal feed (O'Neill 1993) and dietary mineral supplements, which results in contamination of manure, vegetation, soil and water (Marçal et al. 2005; Pompe and Prevendar 2002). In the shoots, Ni, Cr and Pb concentrations were higher than the maximum tolerance limits for food established by the Brazilian legislation (ANVISA, 1965, 1998) and maximum limits suggested by Kabata-Pendias (2010) for the European Union. However, one should realize that the parameters given by Brazilian legislation are the maximum allowable concentrations of elements in grains and vegetables, and legislation provides no specific threshold for the aerial parts of young maize plants, which were evaluated in

this study. It therefore remains to be investigated what the concentrations of heavy metals in the grains after applying vermicompost will be. In any case, it seems advisable to be cautious when choosing cattle manure for vermicomposting.

Nutrient availability in the soil

The higher availability of P, K and Ca in the soil fertilized with vermicompost than in the control treatment (Table 8) was partially related to the contents of these elements in rock dust and manure (Tables 1 and 2). For phosphorus availability, the two to four times higher concentrations in the soil that received gneiss-enriched vermicompost compared to the other treatments can partly be attributed to mineral P sources in gneiss, including apatite (Melo, Castilhos, and Pinto 2009), and to the manure itself. However, the addition of organic matter may also have contributed to increased soil biological activity (Arancon, Edwards, and Bierman 2006) because the increase in available P in the soil that received non-enriched vermicompost was higher than the amount of P in the vermicompost. Organisms play a key role in nutrient absorption and transfer in the soil (Richardson 2001). Among these are phosphate-solubilizing microorganisms that produce phosphatases, and these may have been stimulated by the vermicompost. Furthermore, improved nutrient absorption may have occurred due to the stimulation of mycorrhizal associations and due to root growth (Jakobsen, Leggett, and Richardson 2005). It may also be related to the competing action of Si from the gneiss with phosphate for adsorption sites in the soil (Castro and Crusciol 2013; Tavakkoli, English, and Guppy 2011), thus releasing P, which then becomes available to plants (Carvalho et al. 2001; Prado and Fernandes 1999). The increased P availability in the soil after application of vermicompost and gneiss vermicompost is potentially important, particularly in view of the imminent possibility of shortage of phosphate fertilizers (Cordell, Drangert, and White 2009). Thus, rock powder does not only seem to be an alternative source of P, but also helps in releasing unavailable P from the soil.

Vermicomposting can increase the soil pH, which can be attributed to the excretion of calcium carbonate from the calciferous glands of the pharynx of earthworms when calcium is ingested (Lee 1985). On the one hand, the pH observed in the soil prior to cultivation (Table 5) was similar to the pH in the control and Vc treatments (Table 8) and was near-neutral (6.3), suggesting that the soil that had previously received chemical fertilizers buffered the effect of vermicompost (Soares, Souza, and Cavalheiro 2004). On the other hand, vermicompost with gneiss powder raised the soil pH to 6.7 (see Kiehl 2004; Carvalho 2012; for similar results).

The availability of heavy metals in the soil was low (Table 9), and the levels did not approach the thresholds of reference values of soil quality of uncontaminated soils (Copam, 2011) and maximum limits suggested by Alloway (1995) for the European Union and USA (Table 4). This indicates that the soil immobilizes a large part of the metals added with vermicompost with or without rock powder. The availability and mobilization of heavy metals are controlled by chemical and biochemical processes that are greatly affected by the pH. Aside from the influence of pH, organic matter can generate adsorption sites with high affinity for heavy metals in the soil, acting by ionic bonding and/or as chelating agent in the soil solution (Stevenson 1994).

Conclusions

The participatory learning process facilitated the interaction among farmers and researchers and the execution of the experiment in the field, and resulted in several farmers incorporating the technology to produce vermicompost.

The agricultural use of vermicomposted gneiss powder as a nutrient source is promising in view of it raising the dry shoot matter of maize, the concentration of K, Ca, Mg, and Mn in the shoot dry matter of plants and the levels of available Ca, P and K in the soil after application. Although an increase of heavy metals in shoots of fertilized plants was observed, this cannot be attributed only to

the applied rock powder, but also to manure. Because no threshold values are available for the aerial parts of maize, it is not clear whether these increases will result in increased levels of heavy metals in the grains. No heavy metal wastes were detected in the soil after the experiment.

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