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Original Paper

Crushed Volcanic Rock as Soil Remineralizer: A Strategy to Overcome the Global Fertilizer Crisis

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Transitioning the productive base to a more sustainable agriculture is one of the great challenges of our time. The current conflicts in Eastern Europe have had a major repercussion on the agricultural commodity market with restricted access and a massive cost increase for some fertilizers used in agriculture. This scenario has led to international concern about food shortages, whereby countries that depend on fertilizer imports need to find mechanisms and new technological paths to reduce their dependence on the international market. The use of crushed rock (soil remineralizers) associated with microorganisms is an important alternative in terms of cost reduction, lower impact on the environment and reduction of external dependence on agricultural inputs. The objective of this work was to evaluate the results of different types of inputs for soil fertilization (crushed rock – remineralizer, organic material and conventional – NPK), the production parameters of quinoa culture (*Chenopodium quinoa*) and this nutritional content of the crop. The experiment was carried out in a greenhouse and the data were subjected to analysis of variance, the Dunnett's test, complex contrasts, and multivariate analyses. The results showed significant increases in grain filling and quinoa yields, in soil fertility, and in the nutrient content of the aerial parts of plants treated with remineralizers. The treatments containing a mixture of remineralizers and organic compost were superior to those without these inputs, suggesting positive interaction among these sources. This approach may help toward adopting new technologies, especially with the current undersupply of soluble fertilizers. The use of local geological sources (crushed rock) has the capacity to reduce the dependence on imported fertilizers, thus helping to increase agri-food sovereignty in countries and adhering to the principles of agroecology at the local and global levels.

KEY WORDS: Soil fertility, Agroecology, Stone meal technology, Alternative fertilizers, Crushed rock.

INTRODUCTION

Canada, United States, Morocco, Russia, Belarus, and China control the production and export of the main inputs that make up the NPK (nitrogen, phosphorus, and potassium) formulation in the world (Manning and Theodoro 2018). Several countries are extremely dependent on this international trade and import a substantial amount of K

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fertilizer and agricultural inputs from Russia (FAO 2022). Another important issue is the impressive 800% increase in the use of synthetic nitrogen (N) fertilizers since 1960, according to data from the Intergovernmental Panel on Climate Change (IPCC). These data confirmed that the impact on climate caused by the production and use of these fertilizers will worsen if measures are not taken to reverse this trend (IPCC 2019). The use of synthetic N fertilizers is estimated to increase by about 50% worldwide by 2050, according to the Food and Agriculture Organization of the United Nations (FAO 2018). This scenario has aroused international concern about food shortages, indicating the need to find new technologies that can promote self-sufficiency in agricultural inputs. The use of crushed rock (called remineralizers or REMs in Brazil) is used widely for changing fertility levels and it is being used more and more among small and large farmers (Manning & Theodoro 2018; Theodoro et al., 2021a). This type of soil management is supported by stone meal technology (Leonardos et al. 1987; Theodoro 2000; Hinsinger et al 2001; van Straaten 2006; Theodoro & Leonardos 2015; Carvalho et al. 2018; Korchagin et al. 2019a, 2019b; Ramos et al. 2022).

In general, silicate minerals that form most rocks are made up of macro and micronutrients essential for plants, except N. During weathering, the release of part of these compounds can change soil fertility parameters to form new secondary minerals (Weerasuriya et al. 1993; Leonardos et al. 2000; Manning 2010). Therefore, the application of these materials can be considered as a mechanism for soil rejuvenation (Leonardos et al. 2000; Theodoro & Leonardos 2006). This technology can also be understood as a kind of ‘‘nutrient bank’’, which makes nutrients available more slowly than conventional inputs, since these compounds, made available from the weathering of minerals that form the rocks, are less reactive (van Straaten 2006; Theodoro et al. 2013). On one hand, these sources have a slower release and less concentration than conventional fertilizers, while on the other hand, they behave as multi-nutrient sources (with longer effect), with reduced or no saline effect (Carvalho et al., 2018). They facilitate the use of geological materials available locally and/or regionally, thereby reducing the costs involved in production, logistics, and application of inputs (Carvalho et al. 2018). In many cases, they correct soil acidity and tend to minimize P fixation problems in tropical soil (Leonardos et al. 1987; Elhaissoufi et al. 2022).

Associating materials of geological origin with solubilizing microorganisms of chemical compounds present in the soil (derived from organic matter) can increase the solubilization of nutrients from certain minerals (Carvalho 2012; Tavares et al. 2018; Basak et al. 2020; Yang et al. 2021). This association also favors the supply of N, which is equally important for improving the biochemical and physical characteristics of soils and plants (Zhang et al. 2020). Ramos et al. (2021) showed that the combined use of dacite rock dust and sludge from the dairy industry contributed to the improvement of nutrient concentrations in black oat and maize crop leaves and in soil attributes. This shows that mixtures of sludge with dacite rock dust can be an option to reduce the use of NPK fertilizers, especially for acidic soils. Ramos et al. (2021) stated that the sludge has high reactivity and can promote the solubilization of minerals present in the crushed rock. The method applied by Ramos et al. (2021) proved to be promising and viable for small and medium agricultural farmers because they can benefit from low production costs.

To enhance the nutritional supply of soils, the use of REM has been suggested as a mechanism with large potential for capturing and storing atmospheric CO_2 (Manning et al. 2013; Caner et al., 2014) because it can enhance plant growth (Soares 2018) and it favors the formation of microaggregates (Churchman et al. 2020) or mineral compounds in soils (Beerling et al. 2020), as well as through hybrid mechanisms of CO_2 sequestration, through direct capture of air with synthetic absorbents and with carbon mineralization (Kelemen et al. 2020). For Berg and Banwart (2000), CO_2 capture also depends on the stability of ionic pairs between the cations released from the rocks and the carbonate anion. The inorganic soil sequestration may occur when cations such as Ca and Mg, resulting from the weathering in silicates rocks, react with dissolved CO_2 to form carbonate minerals (Manning et al. 2013).

For Churchman et al. (2020), carbon adsorption is correlated with the presence of clays (derived from crushed rock), which often have crystal structures with large specific surface. When clays (or minerals in the process of changing or that contain defects in their crystalline structures) and microorganisms are present in the soil, an environment is created that favors reactions in the most reactive zones of these minerals. Churchman et al. (2020) reminds us, CO_2 is preferentially removed from the atmosphere and absorbed in soil organic compounds. It is first captured by plants during photosynthesis, fostering their growth and later released into the soil through root exudates and/or their decomposition. This topic still needs further research to arrive at more concrete answers, but it certainly looks very promising, as proposed by Beerling et al. (2020).

Despite their potential, it must be recognized that the use of REM is not simply as a source of nutrients, which is quickly absorbed by cultivated plants, or to accelerate the stages of biological succession and revitalization in soils (Almeida et al. 2007), or even still to sequester and store CO_2. It is not just a system for replacing inputs (chemical fertilizers by crushed rock) or for reducing production costs (Lefebvre et al. 2019); it is a change in the concept of soil fertility management in agroecosystems. Based on this understanding, our research considered the possibility of strengthening the indicators that allow for agroecological transition, which involves, among other actions, the gradual replacement of soluble fertilizers with other inputs that are less impactful from an environmental and economic point of view (Wezel et al. 2009). We also used the principles of agricultural crop rotation as a mechanism to diversify production options according to the needs and the circumstances of producers and agroecosystems, also considering the nutritional quality of food as a mechanism for ensuring food security. Moreover, large amounts of by-products minerals are wasted due to a lack of knowledge about processes and technologies, access to markets, or lack of innovation in the generation of value-added products (Korhonen et al. 2018). To change this trend, it is necessary to generate innovation from the better use of mineral products and agricultural innovation through rational use of natural resources. These premises are in accordance with four goals in the Sustainable Development Goals (SDG) – 2030 Agenda established by the United Nations (UN/SDGs 2020).

Large-scale soil remineralization is needed to address environmental mismanagement, which causes soil to be lost at a much faster rate than it can regenerate naturally. This technology will help increase self-sufficiency in fertilizers for countries that need to import their agricultural inputs. The solution for the agribusiness sector to overcome the shortage in fertilizer imports may lie in the countries themselves. There are several types of rocks that can adequately meet the need of mineral inputs to attend all kinds of agricultures. The use of mineral products derived from ground rocks is based on the hypotheses of stone meal technology. Although there are many types of rocks (e.g., kamafugites, syenites, phonolites, schists) whose chemical and mineralogical compositions are more suitable for soil REMs, basalts (basaltic andesites) were chosen in this study because they are available widely in Brazil and because these rocks are sources of nutrients such as magnesium (Mg), potassium (K), silica (Si) (Anda et al. 2015), especially Ca, which is one of the more important nutrients for quinoa crops (Mujica & Jacobsen 2006). In addition, compared to other rock types, basalts have a mineralogical assembly (pyroxenes, plagioclase and amorphous matrix) that presents dissolution rates at a scale relative to the time required for agricultural crops to grow (Beerling et al. 2018), whereas they are finely crushed. We also considered the granulometric specifications established in Brazilian regulation code IN 05/2016 Brazil (Brazil 2016).

Based on the above premises, the main objective of this article was to evaluate the performance of a type of crushed volcanic rock (basaltic andesite) when mixed with organic compost (OC) to promote the growth and nutrition of quinoa crops. This study also assessed changes in the chemical characteristics of the soil due to the use of REMs, whether combined with organic fertilization or not. The next step of our research assessed the storage and capture of CO_2 from these rocks. This work aimed to highlight changes in soil fertility patterns associated with the use of REMs because this is one of the major necessities in tropical soils, inviting all nations to raise global replication of this technology. Although the results presented in this study pertain to a tropical region, they showed that new technologies can be used to overcome the crisis of soluble fertilizer restriction. This issue has been emphasized increasingly by researchers from various countries, such as China, Australia, England, and others (Manning et al. 2013; Zang et al. 2020; Mbissik et al. 2021; Yang et al. 2021). This technology has the potential to benefit both family and business farmers, especially in countries that are input-dependent on imported fertilizers, such as Brazil and many African countries (Manning & Theodoro 2018; Chiwona et al. 2020; van Straaten 2022).

MATERIALS AND METHODS

Experimental Design

The research was conducted in a greenhouse on the premises of the Agroecological Experiments Laboratory, Faculty of Planaltina (LEAF), University of Brasília (UnB), in the Central-West region of Brazil. Five treatments were tested: OC – derived from a vermicomposting process; soluble mineral fertilizer (NPK); soil REMs – derived from basaltic andesite and a mixture of OC + REM, in addition to the control treatment (C). Each experimental unit consisted of pots (cylindrical vases 63 cm high by 32 cm in diameter) filled with 51 kg of oxisol (dystrophic red latosol), primarily composed of kaolinite and iron and aluminum oxides (Souza and Alves 2003) typical of the Brazilian savannah (Santos et al. 2021). The experiment was set up in a completely randomized design with four replications.

The inputs were incorporated into the soil in each experimental unit using the following dosages: 1.2 kg of OC, equivalent to 47 t ha^{-1} (T1); 120 g of NPK 10–10–10 (T2); 600 g of REM, equivalent to 23.5 t ha^{-1} (T3); 1.2 kg of OC + 600 g of REM (T4); and control (T5). Comparatively, 120 g of NPK is equivalent to 12 g of P_2O_5 pot^{-1} and 12 g of K_2O pot^{-1}, and 600 g of REM is equivalent to 1.62 g of P_2O_5 pot^{-1} and 15 g of K_2O pot^{-1}. The NPK dose was administered according to recommendations for the Brazilian Savanna region. Higher doses of OC and REMs (organo-mineral inputs) were used because the experiment was conducted over a 1-year period. Furthermore, the dose of OC was consistent with those recommended by Ribeiro et al. (1999) for OC and manure in horticultural crops. All the pots were covered with organic matter (straw) to reduce water loss through evaporation and prevent germination of spontaneous plants. The quinoa seeds (*BRS Sytetuba*) were arranged in two grooves and the thinning out process was performed after germination, totaling 20 plants per pot. The pots were irrigated manually during the experimental period (127 days). The treatments were applied six months before the quinoa was sowed.

At the end of the experiment, the height of the plants (from the base to the top of the panicle), the dry mass of the aerial part of the plants, the grain yield, the mass of a thousand grains, and the contents of N, phosphorus (P), K, Ca, Mg, sulfur (S), iron (Fe), manganese (Mn), zinc (Zn), and boron (B) in the vegetative dry matter were all evaluated (Silva 2009). The collected plants were then dried in a greenhouse until they reached a consistent mass. The dry matter of the aerial part (except the grains) was ground in a Wiley mill and submitted to sulfuric and nitric-perchloric digestion (3:1). The N levels were determined by titrimetry (with HCl 0.05 mol l^{-1}) after Kjeldahl distillation was performed. The P and S levels were determined in a molecular absorption spectrophotometer, complexes read at lengths of 660 and 420 nm. The K levels determined in a flame photometer, and the other elements were determined in an atomic absorption spectrophotometer (Silva 2009).

After the plant harvest, the soil in the pots was homogenized and samples were collected for routine chemical analysis (Donagema et al. 2011). The availability of P, K, Fe, Zn, Mn and Cu was evaluated after extraction in 2% citric acid, that of Ca and Mg after extraction in KCl 1 mol l^{-1} and that of S after extraction in a solution of $Ca(H_2PO_4)_2$ in acetic acid. Organic matter levels were determined by titration after oxidation in a K-dichromate solution with no additional heating applied (Donagema et al. 2011).

The REM was obtained from a basaltic andesite from the Vale do Sol Formation (FVS) of rubbly pahoehoe morphology, vertically stacked, belonging to the Serra Geral Group from the Paraná Basin, which makes up a part of the Paraná-Etendeka Magmatic Province (Frank et al. 2009). It was composed of SiO_2 higher than 51 wt% and MgO lower than 5 wt% (Rossetti et al. 2018; Theodoro et al. 2021b). The material used as REM represented the upper portion of the FVS, which is composed of fine-grained rock with vesicles of various sizes (1 mm to 3 cm) filled with milky material, arranged in the form of fibers (probably zeolites and clay minerals as smectites). The granulometric range used in the tests ranged from 0.3 to 2.8 mm, according to Brazilian regulation (Normative Instruction 05/2016) that stipulates the granulometric characteristics of REMs (Brazil, 2016). For the identification, characterization, and evaluation of the potential of this material, total chemistry (X-Ray fluorescence) and petrography analyses were performed with modal determination of its main constituents. The average chemical composition of the rocks is shown in Table 1.

The rock consisted of plagioclase phenocrysts and lesser amounts of clinopyroxene, in a fine to microcrystalline matrix with incipient weathering, which presented fine plagioclase crystals and opaque

Table 1. Average content of the main silicate components of the REM analyzed by x-ray fluorescence

SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	K_2O (%)	P_2O_5 (%)	Na_2O (%)	TiO_2 (%)	MnO (%)	LOI* (%)
56.8	14.4	10.2	7.04	3.91	2.5	0.27	2.68	1.29	0.15	0.53
As (ppm)	Hg (ppm)	Pb (ppm)	Cd (ppm)	Co (ppm)	Cu (ppm)	Fe (ppm)	Mo (ppm)	Ni (ppm)	Zn (ppm)	V (ppm)
< 1	< 0.05	3.6	0.04	31.2	51.2	2.72	7.23	6.9	46.0	14.63

*LOI = Lost of Ignition

minerals (magnetite and ilmenite), identified by X-ray diffractometry (using the *RIGAKU Ultima IV* diffractometer). Part of the matrix resulted from the devitrification of the original glass, the most common constituent of volcanic rocks of around 32.4%, followed by plagioclase minerals (30%), clinopyroxenes (22.2%), clay minerals (6.6%), opaque minerals and quartz (Fig. 1).

The OC was obtained by vermicomposting, and the fertility analysis showed expressive contents of available Ca^{2+}, Mg^{2+}, P and K (5.6 and 7.0 $cmol_c$ dm^{-3}, and 692 and 296 mg dm^{-3} respectively). The latosol had very low mean concentrations of these nutrients (0.36 and 0.13 $cmol_c$ dm^{-3}, and 4.32 and 29.18 mg dm^{-3}, respectively), in addition to low levels of organic matter, and an acid pH of 5.4 on average (Table 2).

STATISTICAL METHODS

The data were subjected to analysis of variance (ANOVA) and the averages were compared using Dunnett's test and contrast tests. The normality conditions of the residuals, homogeneity of the variances, and the presence of *outliers* were verified by the Jarque–Bera test (Jarque and Bera 1980), the Levene-Brown-Forsythe test and the generalized ESD test (Rosner 1983), respectively. Treatments with REMs were compared against treatments without REMs by a contrast ($\hat{C}_1$), whose significance was assessed by the modified Bonferroni test (Conagin 2001). Contrast was defined by the expression $\hat{C}_1 = (T3_{REM} + T4_{OC+REM}) - (T5_{Control} + T1_{OC})$. The magnitude of the $\hat{C}_1$ effect was estimated using the d-Cohen statistic (Cohen 1988). Additionally, to partially overcome the low sensitivity of the univariate tests, the data were subjected to multivariate analysis using the Mulamba–Mock index. The analyses were performed using the SPEED Stat 2.4 software (Carvalho et al. 2020).

RESULTS

Based on the textural, lithochemical and mineralogical characteristics of the REM, we concluded that this type of geological material is appropriate for remineralization of soils, as suggested by Hartmann (2014), especially because these constituents are often highly weatherable (White and Buss 2013). The presence of smectites – characterized as saponite (X-ray diffractometry) – increases cation-exchange capacity (CEC) and favors soil moisture retention (Theodoro et al. 2020). These minerals are associated with the innumerable vesicles that can be found in the upper part of basalt flows (Bergmann 2013), making these intervals more suitable for agricultural use compared to the layers where they are rarer. The dominance of different silicates can facilitate pH neutralization efficiently, acting in a similar fashion to liming process (Melo et al. 2012; Shamshuddi et al. 2012; Santos et al. 2021). However, after one year of research, we were unable to find significant differences for this parameter (5.4 at the beginning and 5.7 at the end).

We found that the treatments differed from each other in all the evaluated growth parameters (Table 3); treatments with REMs were superior to those with no REMs ($\hat{C}_1$) (Fig. 2). Quinoa grain yield in treatments with REMs was on average 115% higher than those with no REMs ($\hat{C}_1$), with emphasis on the OC + REM treatment. The parameter that possibly had the most influence on this performance was grain size because the mass of 1000 grains (M1000G) was 76% higher in OC + REM treatment than it was in the control treatment (Fig. 2).

Some nutrient contents in plants were also influenced significantly by the treatments (Table 3). The REM + OC treatment was one example; it promoted an increase of 98% in Ca content and 197% in Mn content in the aerial part of the plants compared to the control (Fig. 2). It is likely that the increase of Ca in the aerial part of the plants was a

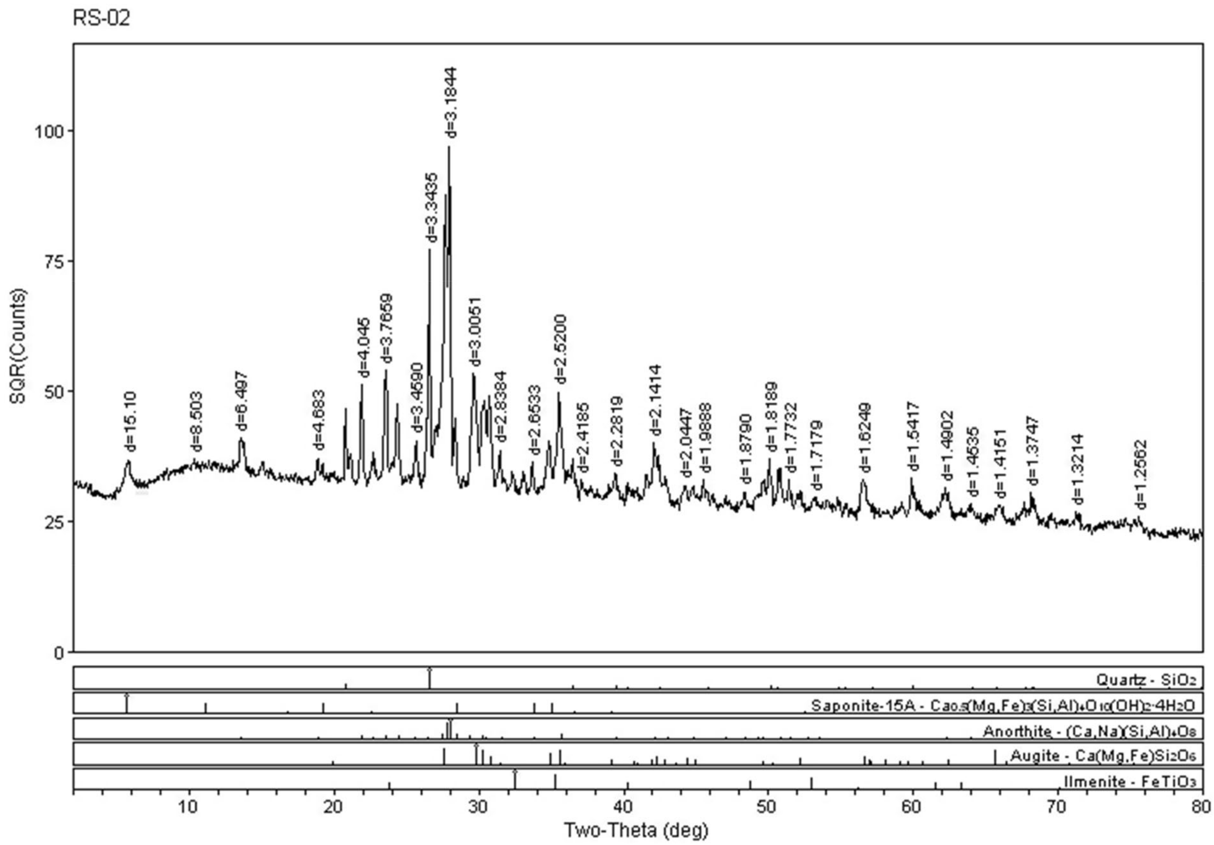


Figure 1. Some mineralogical components of a basaltic andesite sample (X-ray diffractometry).

Table 2. Initial levels of macro- and micronutrients in soil used in experimental units (pots)

P (mg dm^{-3})	K (mg dm^{-3})	S (mg dm^{-3})	Ca (cmol$_c$ dm^{-3})	Mg (cmol$_c$ dm^{-3})	CEC pH 7 (cmol$_c$ dm^{-3})	Organic matter (dag kg^{-1})
4.32	29.18	11.18	0.36	0.13	5.25	2.28
pH [H_2O (2.5:1)]	V (%)	B (mg dm^{-3})	Zn (mg dm^{-3})	Fe (mg dm^{-3})	Mn (mg dm^{-3})	Cu (mg dm^{-3})
5.4	11	0.35	< 0.1	123.8	6.52	0.63

result of the greater availability of this nutrient from the solubilization process of the main minerals in the basaltic andesite, especially those that are more easily weathered. This increased assimilatio($\hat{C}_1$n of Ca^{+2} in the plants confirmed the hypothesis that the nutrients derived from ground rock are assimilated enough for plant development in a short term. On average, treatments with REM had more of these nutrient contents than those with no REM) (Fig. 2). These effects can be considered of great magnitude based on the d-Cohen statistics, both greater than 1.20 for the contrast $\hat{C}_1$ (Table 3). For the other nutrients we evaluated, there was insufficient statistical evidence to determine whether the treatments had influenced the observed contents or not.

The results are consistent with those obtained by Kelland et al. (2020), who used crushed basalt to evaluate the absorption and accumulation of some nutrients in the sorghum crop. Unlike the research of these authors, our research was not able to verify

Table 3. Overall mean, value of F statistic, coefficient of variation (C.V.) and magnitude of contrast effect $\hat{C}_1$ (d-Cohen statistic) for growth parameters and nutrient contents in shoots in quinoa culture

	Shoot (g pot^{-1})	Prod. (g pot^{-1})	M1000G (g)	Height (cm)	N (g pot^{-1})	P (g pot^{-1})	K (g pot^{-1})
General mean	202	26.75	2.29	118	3.75	0.4	3.91
F (Treatments)	3.32*	6.57**	14.08**	4.15*	1.23^{Ns}	1.09^{Ns}	2.65^{Ns}
C.V.(%)	20.6	29.5	10.6	3.8	33.16	33.37	30.19
d-Cohen ($\hat{C}_1$)	1.64	2.46	2.96	1.6	0.99	0.82	1.34
	Ca (g pot^{-1})	Mg (g pot^{-1})	S (g pot^{-1})	Mn (mg pot^{-1})	Fe (mg pot^{-1})	Zn (mg pot^{-1})	B (mg pot^{-1})
General mean	1.72	0.77	0.26	8.36	13.65	8.65	4.67
F (Treatments)	3.07*	1.55^{Ns}	2.03^{Ns}	3.06*	0.65^{Ns}	1.4^{Ns}	2.13^{Ns}
C.V.(%)	35.33	38.15	27.44	48.46	30.1	29.77	33.43
d-Cohen ($\hat{C}_1$)	1.32	0.85	1.15	1.68	0.45	0.6	1.09

*Statistically significant difference ($p < 0.05$) between treatments. **Statistically significant difference ($p < 0.01$) between treatments. Ns: Not significant

an increase in K. This was probably because the basaltic andesite of the Paraná basin had lower K_2O contents (2.5%) compared to the contents in the basalts (Central Oregon) used in their research (3.5% of K_2O).

At the end of the experiment, some of the nutrient contents available in the soil also differed between treatments (Table 4). When compared to the control, the treatment with NPK increased the availability of S significantly in the soil and the treatment with OC increased the availability of Mg in the soil by 38% (Fig. 3). There was insufficient statistical evidence to determine that REM treatments, on average, differed from treatments with no REMs ($\hat{C}_1$) for these parameters (Table 4, Fig. 3).

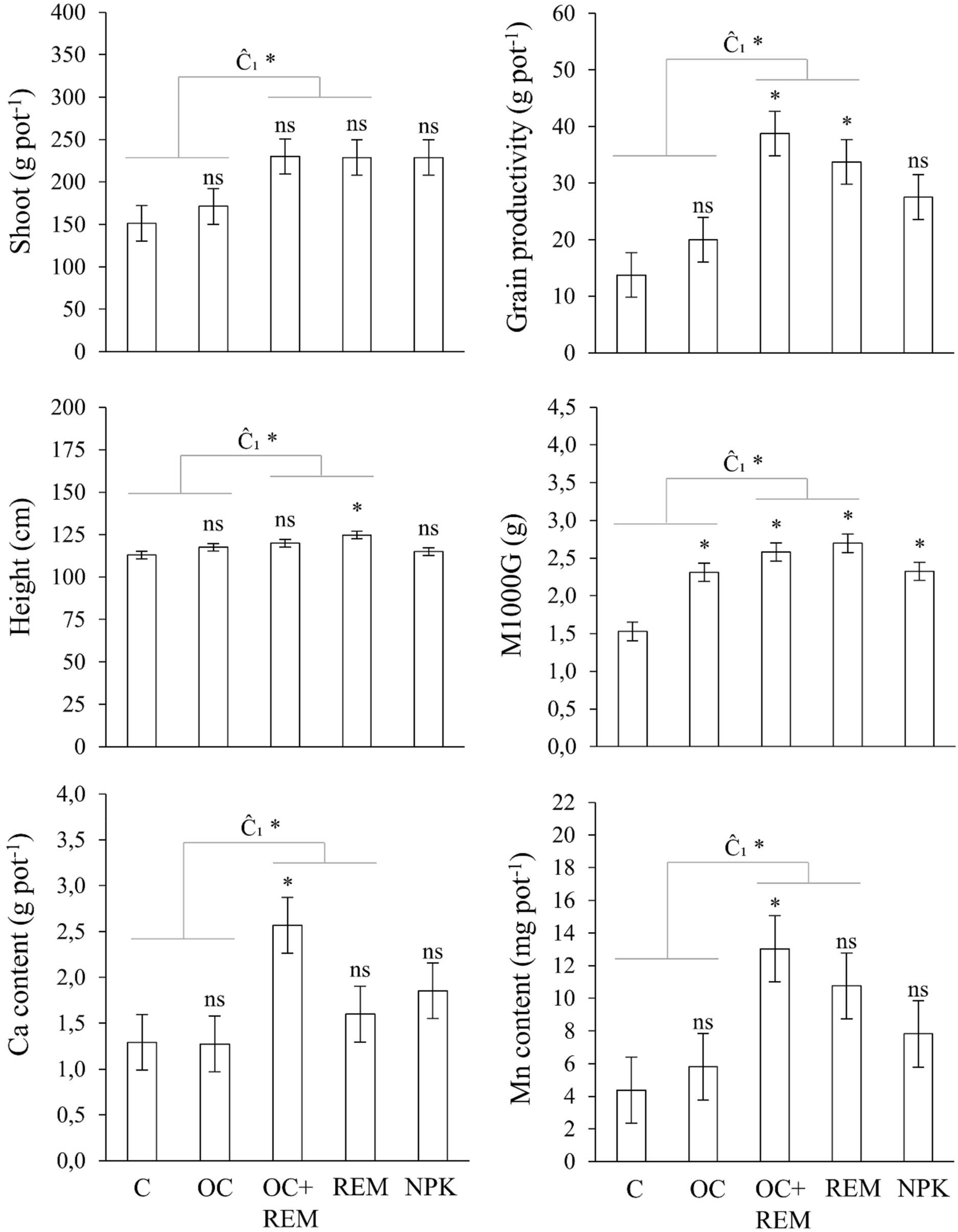
The Mulamba–Mock multivariate index showed significant differences between the evaluated soil parameters (Fig. 4). When considering the main soil parameters evaluated, the index showed that treatments containing REMs were, on average, superior to treatments with no REMs ($\hat{C}_1$) (Fig. 4A). The same pattern was observed for the index built with the nutrient contents in the aerial part of the plants, with emphasis on the OC + REM treatment (Fig. 4B).

DISCUSSION

Many previous studies on the use of basalt rock dust (Dalmora et al. 2016; Ramos et al. 2020; 2022; Beerling et al. 2020) were aimed primarily at finding indicators on nutrient supply, especially K (Manning 2010; Setiawati & Mutmainnah 2016; Mbissik et al. 2021; Santos et al. 2021), which is a limiting factor for agricultural production in tropical soils (Leonardos et al. 1987) in predominantly dystrophic environments (Jacobson and Bustamante 2019). Our hypothesis assumed that the use of REMs would change the levels of some nutrients available in the soil after the application of different inputs (especially crushed basaltic andesite mixed [or not] with OC) in the development and productivity of the quinoa crop and the nutrient content of these plants.

The best performance of REM and/or OC + REM treatments observed for various parameters (Fig. 4B) was consistent with other studies (Hinsinger et al. 2001; Badr 2006; Setiawati & Mutmainnah 2016; Sarkar et al 2021; Yang et al. 2021), suggesting collaborative influence between the mineral supply provided by crushed rocks and microorganisms derived from different organic sources. It is likely that microbial processes favored the increase in the hydrolysis rates of minerals (plagioclases, pyroxenes, and saponite) containing these chemical compounds through chelating agents and/or organic acids, as suggested by Kelemen et al. (2020).

From a univariate perspective, our results did not show that the addition of REM (mixed or not mixed with organic fertilizer) increased the supply of nutrients in the soil. When analyzing from a perspective of multivariate indicators (Mulamba–Mock index), the chemical parameters of the soil underwent a significant change in REM treatment when compared to the control (Fig. 4A). This fact is consistent with evidence presented by Tchouankoue et al. (2015), Ramos et al. (2020) and Tonello et al. (2021). The use of volcanic rocks, rich in Ca and silicates, can reduce the need for liming, which is used recurrently to neutralize the acidity of tropical


Shoot (g pot^{-1})
Grain productivity (g pot^{-1})
Height (cm)
M1000G (g)
Ca content (g pot^{-1})
Mn content (mg pot^{-1})
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◀**Figure 2.** Quinoa growth parameters (aerial dry mass, grain yield, plant height and thousand-grain mass) and Ca and Mn contents in the aerial part of plants as a function of the application of organic compost (OC), OC with basaltic andesite (OC + Rock), only crushed basaltic andesite (Rock), only mineral fertilization (NPK) and control. Measurements followed by * differ from the control according to Dunnett's test at 5% error probability. Contrasts (C_1 = (Rock + OC + Rock) − (Control + OC)) followed by * differ from zero by the modified Bonferroni test at 5% error probability. Measurements (n = 4) ± standard error of the experiment. Graphics made using SPEED stat and PowerPoint.

soils, which also implies potential for the reduction of CO_2 emissions of the productive sector.

The positive interaction between organic fertilizers and REMs still needs to be studied and understood further because the maximum effect of the REMs is still not clear enough, or there is only a sum of the beneficial effects of both fertilizers. Additionally, in the case of organic fertilizers commercialized with REMs already mixed in, it is important to note that the rocks increase greatly the density of the final mixture because they only occupy the porous spaces of the organic material (Tavares et al. 2018). After all, adding certain amounts of crushed rock to organic fertilizer does not increase its volume, only it's mass. This means that fertilizer with organic materials enriched with REMs must be recommended by volume and not by mass.

Proof that REM treatments influence plant nutrition positively (Fig. 4B) may be better associated with the sum of the effects on accumulations of K, Ca, S, Mn and B, all with high *effect size* (d-Cohen > 1.0 for $\hat{C}\hat{C}_1$(Table 3). This effect, evidenced by the higher power of the multivariate analysis in relation to the univariate analysis, may result in better plant growth from the improved nutritional balance that multi-nutrient sources provide. Considering that the quinoa crop has a greater demand for P, K, Ca, Zn, Fe, and Mg (Spehar et al. 2011), and that the REM and OC used in treatments have expressive contents of all these nutrients, we can assume that the best results in terms of production parameters (Fig. 2) in treatments with REM and/or REM + CO (115% higher) compared to those that did not contain these sources (control and NPK) were due to the more diverse supply of nutrient sources derived from crushed basaltic an-

Table 4. General average, F statistic value, coefficient of variation (C.V.) and magnitude of the contrast effect $\hat{C}_1$ (d-Cohen statistic) for the evaluated soil parameters

	P (mg dm^{-3})	K (mg dm^{-3})	S (mg dm^{-3})	Ca (cmolc dm^{-3})	Mg (cmolc dm^{-3})	CEC pH 7 (cmolc dm^{-3})	Organic Matter (dag kg^{-1})
General mean	45.45	252.46	42.01	8.75	1.56	11.19	4.68
F (Treatments)	1.33^{Ns}	1.5^{Ns}	5.56**	0.25^{Ns}	3.4*	0.51^{Ns}	1.3^{Ns}
C.V.(%)	45.9	16.1	19.1	21.3	16.6	17.2	7.69
d-Cohen ($\hat{C}_1$)	0.81	0.77	0.31	0.26	0.16	0.22	0.11
	pH [H_2O (2.5:1)]	pH ($CaCl_2$)	B (mg dm^{-3})	Zn (mg dm^{-3})	Fe (mg dm^{-3})	Mn (mg dm^{-3})	Cu (mg dm^{-3})
General mean	7.63	7.07	2.18	4.99	65.52	15.27	0.18
F (Treatments)	0.57^{Ns}	0.96^{Ns}	2.98^{Ns}	1.17^{Ns}	3.05^{Ns}	2.03^{Ns}	2.1^{Ns}
C.V.(%)	2.68	1.8	16.8	49.3	55.8	28.4	114.4
d-Cohen ($\hat{C}_1$)	0.33	0.15	0.37	0.87	0.93	1.22	0.54

*Statistically significant difference ($p < 0.05$) between treatments. **Statistically significant difference ($p < 0.01$) between treatments. Ns: Not significant

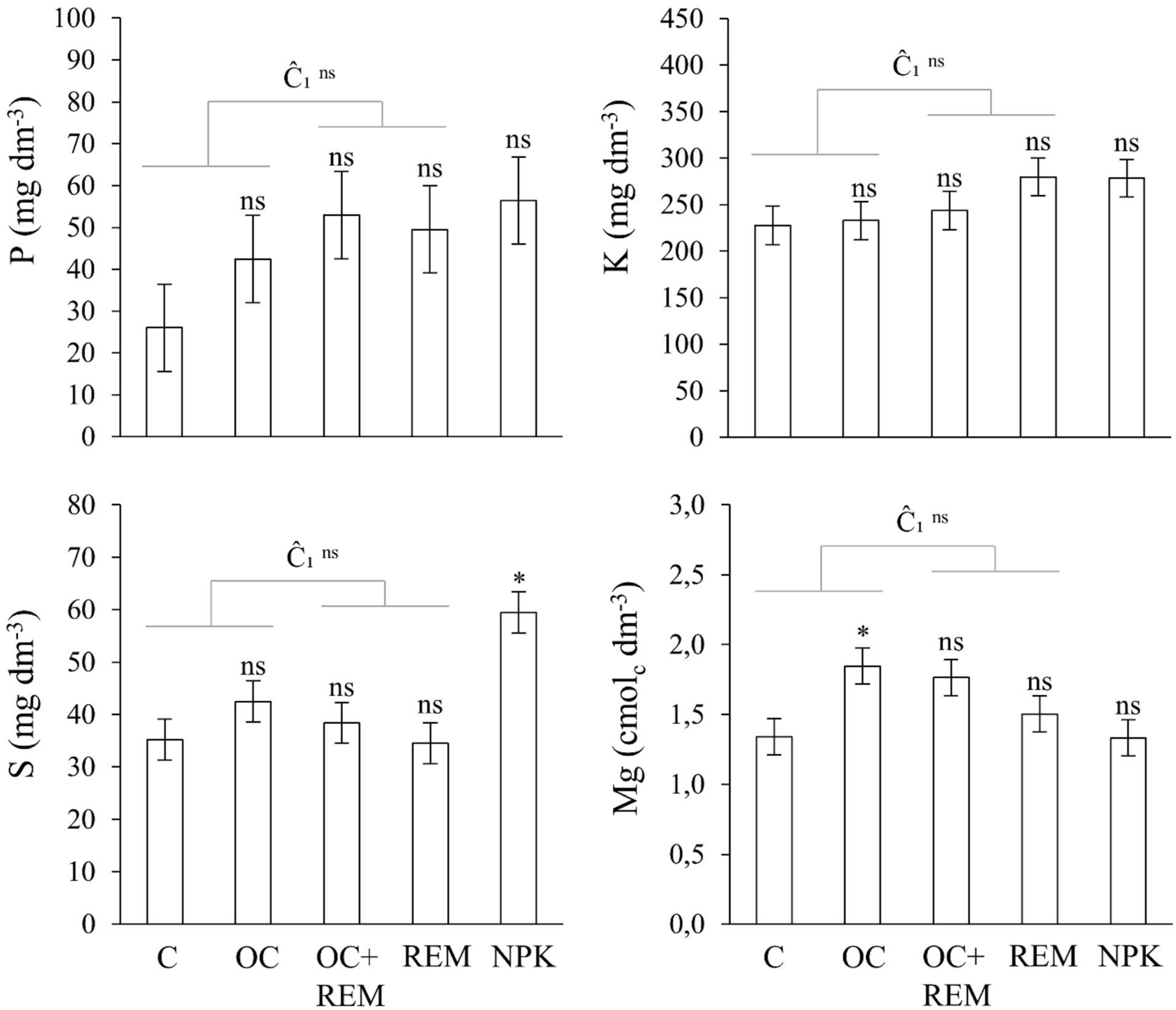

Figure 3. Availability of macronutrients P, K, S and Mg in the soil as a function of the application of organic compost (OC), OC + REM (OC + REM), only REM, only NPK and Control. Measurements followed by * differ from control according to Dunnett's test at 5% error probability. Contrasts (C1 = (REM + OC + REM) – (Control + OC)) followed by * differ from zero by the modified Bonferroni test at 5% error probability. Measurements (n = 4) ± standard error of the experiment. Graphics made using SPEED stat and PowerPoint.

desite in association with microorganisms present in organic compounds, as suggest by Sarkar et al (2021)

The more expressive presence of Ca and Mn in the aerial part of the plants verified in the treatments containing REM reinforce the hypothesis that the plants were able to extract one of the most abundant components (i.e., Ca) from the basaltic andesite because the mineralization of Ca from organic sources is not as fast as from other nutrients (Gama-Rodrigues et al. 2007; Ventura et al. 2010; Korchagin et al., 2019a, 2019b). This result suggests that the transfer of nutrients available in crushed basaltic andesite may occur on the time scale of the plant development cycle, as suggested by Kelland et al. (2020) and Gonçalves et al. (2022). This double offer derived from the two different sources (mineral and organic) favored the plant's ability to assimilate these nutrients more effectively in treatments containing crushed basaltic andesite or the organic-mineral mixture (Fig. 2), although we have not identified the specific source of Ca.

Regarding the greater accumulation of Mn by plants in the OC + REM treatment, Bazak et al. (2020) also observed that this micronutrient, together with Fe, is more easily solubilized from minerals when in the presence of biological activity.

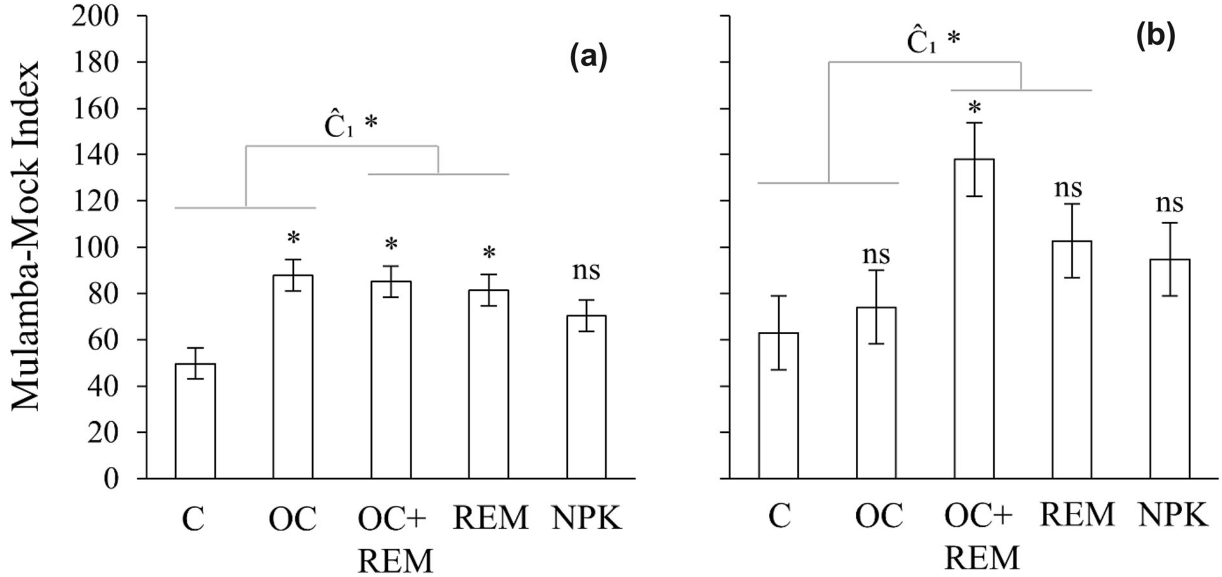

Figure 4. Mulamba–Mock multivariate index of soil chemical parameters(A) or plant shoot contents (B) as a function of application of organic compost (OC), OC + REM (OC + REM), only crushed basaltic andesite (REM), only NPK fertilization, and control. Measurements followed by * differ from control according to Dunnett's test at 5% error probability. Contrast (C1 = (REM + OC + REM) – (Control + OC.)) followed by * differs from zero by the modified Bonferroni test at 5% error probability. Measurements (n = 4) ± standard error of the experiment. Graphics made using SPEED stat and PowerPoint.

This effect may be linked to changes in soil pH, production of siderophores by microbiota, or even to the oxidation of organic matter (Luján et al. 2015; Eshaghi et al. 2019). Still regarding the macronutrient levels in the aerial part of the plants, it is highlighted that even the P levels, which had a more prominent soluble source (NPK), did not increase in the soil or in the plants, suggesting the high capacity of P fixation in oxisols, as already verified widely in the studies of Jacobson and Bustamante (2019) and Roy et al. (2016). Another hypothesis, verified in other studies (Theodoro et al. 2020; Kronberg et al. (1987), refers to the possible capture of P atoms and, secondly, of Mg, in the inter-layer structure of kaolinitic clays present in oxisols. Although related indirectly to P, the levels of S showed significant differences in the treatment containing NPK when compared to the control. This difference can be explained by the displacement effect of S adsorbed in the soil by the addition of P with greater solubility than NPK (Alvarez et al. 2007).

The use of REM derived from crushed rock has been applied consistently in Brazil, mainly due to the high costs of soluble fertilizers, but also due to the positive production results which continue to be reported in tropical soils. Our research confirmed that the use of REM, with or without the presence of microorganisms derived from organic sources, is an effective collaborative form for supplying soil with nutrients (especially K, Ca, Mg and micronutrients) as well as promoting increased productivity.

The assimilation of nutrients occurred over an acceptable time scale to promote plant growth and nutrition, which corroborates other studies reporting on this capacity. This ability shows that using local and regional crushed rock meets the demands of different productive realities and could significantly reduce the dependence on expensive soluble fertilizers, controlled by only a handful of countries that dominate the international market. This aspect is especially important nowadays due to the restricted access to fertilizers and the war in Eastern Europe. Perhaps it is time for the world to look toward local solutions that can contribute to global productive food security.

CONCLUSION

Our results showed that the use of crushed rock and organic material promote changes in soil fertility and in the development of agricultural crops. In the specific case of quinoa crops, we observed that better nutritional balance, derived from multi-nutrient organo-mineral sources, facilitated plant growth and yield. The greater demand for nutrients such as K, P, Ca, Zn, Fe, and Mg required by quinoa crops may have been met more effectively as the REMs (basaltic andesite) used and the organic compound (source of multi-nutrients) met these nutritional demands and resulted in better productive indicators (about 115% higher) when compared to the control and NPK treatments.

Statistical analysis with multivariate index (Mulamba–Mock) showed that treatments containing REMs were, on average, superior to those without REMs ($\hat{C}_1$). The same pattern was observed for the index constructed with the nutrient contents in the aerial part of the plants, particularly the OC + REM treatment. The positive interactions between these sources indicate great potential for these nutrient sources in times when fertilizer is scarce.

Although this research presents results for a tropical region, it points out and reinforces options that have adherence to new technologies routes to face the global crisis of soluble fertilizer restriction.

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DECLARATIONS

Conflict of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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