Communications in Soil Science and Plant Analysis

ISSN: 0010-3624 (Print) 1532-2416 (Online) Journal homepage: https://www.tandfonline.com/loi/lcss20

# Can Dunite Promote Physiological Changes, Magnesium Nutrition and Increased Corn Grain Yield?

C. A. C. Crusciol, L. G. Moretti, J. W. Bossolani, A. Moreira, P. H. Micheri & R. Rossi

COMMUNICATIONS IN SOIL SCIENCE AND PLANT ANALYSIS
https://doi.org/10.1080/00103624.2019.1659304

# Can Dunite Promote Physiological Changes, Magnesium Nutrition and Increased Corn Grain Yield?

C. A. C. Crusciol [a], L. G. Moretti[a], J. W. Bossolani[a], A. Moreira[b], P. H. Micheri[a], and R. Rossi[a]

[a]Department of Crop Science, São Paulo State University (UNESP), Botucatu, São Paulo State, Brazil; [b]Department of Soil Science, Embrapa Soja, Londrina, Paraná State, Brazil

**ABSTRACT**
Several efforts have been made in recent years to mitigate the different environmental impacts related to agricultural activities. Rock dust technology is an important soil remineralization mechanism for sustainable tropical agriculture. The objective of this study was to evaluate the effect of dunite rates on magnesium (Mg), silicium (Si), reducing sugars, sucrose and foliar starch, soil chemical attributes and corn yield [*Zea mays* L.] in two soil types. The treatments consisted of five dunite rates (0, 42, 208, 542, and 1542 mg $kg^{-1}$) in a clayey soil and five dunite rates (0, 150, 238, 411, and 933 mg $kg^{-1}$) in a sandy soil. In both crops and soils, the content of Mg, Si, leaf reducing sugars, pH, Mg and Si of the soil and productivity components presented a positive response as a function of an increase in the input dose. However, the higher Mg nutrition resulted in lower levels of sucrose and foliar starch. The better plant partitioning of metabolites led to better development, filling and yield of corn grains.

**ARTICLE HISTORY**
Received 15 July 2019
Accepted 20 August 2019

**KEYWORD**
*Zea mays*; magnesium fertilization; silicium; volcanic rock powders; natural soil fertilizers

## Introduction

Brazil is currently one of the world's largest producers of corn, with a production of approximately 97 million tons, and the second largest exporting country (CONAB (National Supply Company) 2019). The growing demand is due to its wide use in food and feed. Corn agribusiness is the sixth largest income generating activity in the national agricultural economy (CONAB (National Supply Company) 2019). Soil fertility management and crop fertilization, which determine the highest economic yields, are variable for each region, according to the chemical and granulometric properties of soils. Thus, dunite is a viable option in agriculture because this is a nutrient source for the crop and can be used as a magnesium (Mg) source for several crops (Moretti et al. 2019).

According to Ramos et al. (2015), given that Brazil is one of the largest suppliers of food in the world, study of volcanic rock dust as a potential fertilizer with respect to the content and release of nutrients and to the economic and market viability is still required to provide the development of sustainability policies for mining activity and food production. According to Assis and Dias (2007), dunite is an igneous rock, which is essentially a peridotite, magmatic or eruptive material, consisting mostly of olivine $(MgFe)_2SiO_4$, containing approximately 40% Mg oxide (MgO) and 34% Si oxide ($SiO_2$). The application of rock dust for remineralizing the soil is related to its mineral characteristics and its interaction with the environment in which it will be applied to improve the conditions of soil fertility (Moreira et al. 2006; Ramos et al. 2017).

The role of Mg in several vital functions in plants is well understood. A deficiency of Mg in plants may be caused by soil reserve depletion but can also be induced by low Mg assimilation by the roots due to competitive inhibition caused by an imbalance of some cations, such as calcium (Ca), potassium (K), manganese (Mn), and zinc (Zn) (Canizella et al. 2018; Crusciol et al. 2016; Kwano

**CONTACT** A. Moreira adonismoreira66@gmail.com Department of Soil Science, Embrapa Soja, Londrina, Paraná State, Brazil
Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/lcss.

et al. 2017; Tränkner, Tavakol, and Jákli 2018). Reduced transport and accumulation of carbohydrates in Mg-deficient leaves cause alterations in photosynthetic carbon metabolism and restrict $CO_2$ fixation (Farhat et al. 2016; Kwano et al. 2017).

Magnesium is closely linked to the partitioning between the synthesis of starch, transport of triose phosphates in the cytosol and the formation of sucrose, so that low availability of Mg leads to a reduction in cytosolic glucose-fructose bonds (Ceylan et al. 2016). However, the accumulation of carbohydrates in leaves is an evident response that is part of a signaling system that still needs further studies to understand the role of Mg in photoassimilate phloem loading and the accumulation of metabolites in deficient leaves. Thus, this study aimed to evaluate the effect of fertilization with dunite on the nutritional, metabolic and grain yield of corn, as well as on the soil chemical attributes in two soils with different clay contents.

## Materials and methods

A greenhouse experiment was carried out in the 2016–2017 cropping season at the College of Agricultural Science, Department of Crop Science, Botucatu, São Paulo State, Brazil. The soils used in the experiment were two Rhodic Hapludoxes (Santos et al. 2013) with clayey and sandy textures. The clayey soil contained 602 g $kg^{-1}$ clay and 281 g $kg^{-1}$ sand, and the sandy soil contained 259 g $kg^{-1}$ clay and 724 g $kg^{-1}$ sand. The soil chemical attributes (0.0–0.2 m depth) were determined according to van Raij et al. (2001), as demonstrated in Table 1

Dunite presents the following chemical attributes: 24% Mg (40% MgO) and 16% Si (34% $SiO_2$). The experimental design was completely randomized, with four replicates for both soils. The treatments consisted of the application of five dunite rates: 0, 42, 208, 542 and 1542 mg $kg^{-1}$ for clayey soil, and five dunite rates: 0, 150, 238, 411, and 933 mg $kg^{-1}$ for sandy soil. Pots with a 20-L capacity were used in both experiments.

Nutrients were supplied as 200 mg $kg^{-1}$ – N and P, 150 mg $kg^{-1}$ ⁻ K, 15.0 mg $kg^{-1}$ – S, 5.0 mg $kg^{-1}$ – Zn, 1.5 mg $kg^{-1}$ – B (boron), and 0.5 mg $kg^{-1}$ – Cu (copper). The soil water content in pots was corrected to −0.01 MPa (field capacity), corresponding to 112 g $kg^{-1}$, respecting the equilibration period (60 to 100% field capacity). Five seeds (Dow 2B 587 PW hybrid) were sown per

**Table 1.** Chemical and granulometry characteristics of soils (0–0.2-m depth).

| | Soils | |
|---|---|---|
| Soil properties | Clayey Soil | Sandy Soil |
| pH ($CaCl_2$) | 5.2 | 5.4 |
| P ($_{resin}$), mg $dm^{-3}$ | 6 | 3 |
| S.O.M., g $dm^{-3a}$ | 25.2 | 13.1 |
| $Ca^{2+}$, $mmol_c$ $dm^{-3}$ | 35 | 18 |
| $Mg^{2+}$, $mmol_c$ $dm^{-3}$ | 8 | 2 |
| $K^+$, $mmol_c$ $dm^{-3}$ | 0.7 | 0.5 |
| $H^+$+$Al^{3+}$, $mmol_c$ $dm^{-3}$ | 29 | 18 |
| $Al^{3+}$, $mmol_c$ $dm^{-3}$ | 0 | 0 |
| S-$SO_4^{2-}$, mg $dm^{-3}$ | 2.6 | 1.5 |
| Fe, mg $dm^{-3}$ | 20 | 35 |
| Cu, mg $dm^{-3}$ | 8.4 | 1.6 |
| Mn, mg $dm^{-3}$ | 15.3 | 1.9 |
| Zn, mg $dm^{-3}$ | 0.9 | 0.3 |
| B, mg $dm^{-3}$ | 0.4 | 0.3 |
| Si, mg $dm^{-3}$ | 13 | 7 |
| CEC, $mmol_c$ $dm^{-‡}$ | 73 | 39 |
| BS, (V), %[§] | 60 | 53 |
| Clay, g $kg^{-1}$ | 602 | 259 |
| Sandy, g $kg^{-1}$ | 281 | 724 |
| Silte, g $kg^{-1}$ | 117 | 17 |

[a]Soil organic matter; [‡]Cation exchange capacity; [§]Base saturation

treatment, and three plants were left per pot after emergence. Four reference pots were weighed every four days, and as needed, distilled sterile water was added to return the water content to field capacity (–0.01 MPa).

Leaves were collected and ground in a Wiley-type mill coupled to a 1-mm sieve. Then, the Mg and Si contents were determined (Malavolta, Vitti, and Oliveira 1997). The partitioning of carbohydrates as reducing sugars (glucose and fructose), sucrose and starch content, measured in the dry matter of leaves, was determined according to the methodology of Nelson (1944). The readings were performed using a spectrophotometer at 535 nm. At the same time as the foliar diagnosis, two plants were collected for dry mass analysis.

The plants were grown until the end of the cycle, and the mass of 100 grains was determined by means of precision scale weighing, value correction (13% on a wet basis) and the number of grains per ear. The grain yield was expressed as g plant$^{-1}$. After harvest, a soil sample of each pot was collected, and the pH, Mg and Si contents were analyzed according to van Raij et al. (2001).

## Statistical analysis

All data were initially tested for normality using the Shapiro-Wilk test (Shapiro and Wilk 1965) from the UNIVARIATE procedure of SAS version 9.3 (SAS Institute 2015), and the results indicated that all data were distributed normally ($W \geq 0.90$). The data were submitted to analysis of variance (ANOVA) and F-test ($p \leq 0.05$). A polynomial regression analysis was performed to determine dunite-rate response curves for measured corn and soil traits, where significant regression equations with the highest coefficients of determination were selected.

## Results and discussion

The Mg and Si leaf contents of the corn crop increased linearly as a function of the increase in the dunite rates, regardless of soil texture. The maximal contents obtained for these nutrients in corn leaves were 3.4 g kg$^{-1}$ Mg and 18.3 g kg$^{-1}$ Si when grown in clayey soil (Figure 1a and b) and 3.9 g kg$^{-1}$ Mg and 15.3 g kg$^{-1}$ Si when grown in sandy soil (Figure 1c and d). Dunite is a mineral material that undergoes heating at temperatures close to 400°C, a process known as sepertinization. As a result, approximately 90% of the magnesium and silica minerals present are hydrated, thus increasing their solubility in the system, making them more easily absorbed by the plant root system (Fernandes, Luz, and Castilhos 2010).

Mg is the most abundant divalent cation in the plant cytosol. It has a fundamental role in plants and several other organisms due to its ability to interact with nucleophilic binders (Cakmak and Kirkby 2008), as well as being the central atom of the chlorophyll molecule and being involved in numerous photosynthetic processes (Ceylan et al. 2016). It is known to be the largest enzymatic activator, of enzymes such as RNA polymerases, ATPases, protein kinases, phosphatases, glutathione synthetase and carboxylases (Tränkner, Tavakol, and Jákli 2018). Small variations in the concentrations of this element in chloroplasts are sufficient to alter the activity of several important enzymes of plant metabolism (Wang et al. 2012). Considering the bottleneck of the Mg supply for agricultural systems, dunite is an important source of this element. Furthermore, due to its behavior similar to magnesium silicate, it has a high potential of supplying Si to the soil.

In general, most grass plants (e.g., corn, wheat, triticale, ryegrass, sorghum, rye and barley) are known as Si-accumulating species, although root uptake is inferior to rice (Nikolic et al. 2007). The first Si transporters were studied in rice plants (Ma et al. 2007). They are responsible for infiltration (Lsi1) and silicon efflux (Lsi2). These same carriers were also identified in barley and corn (Chiba et al. 2009; Mitani et al. 2009). In the case of corn, the ZmLsi1 transporters are located in the epidermal, hypodermic and cortical cells, and their expression levels are not influenced by the Si supply (Chiba et al. 2009).

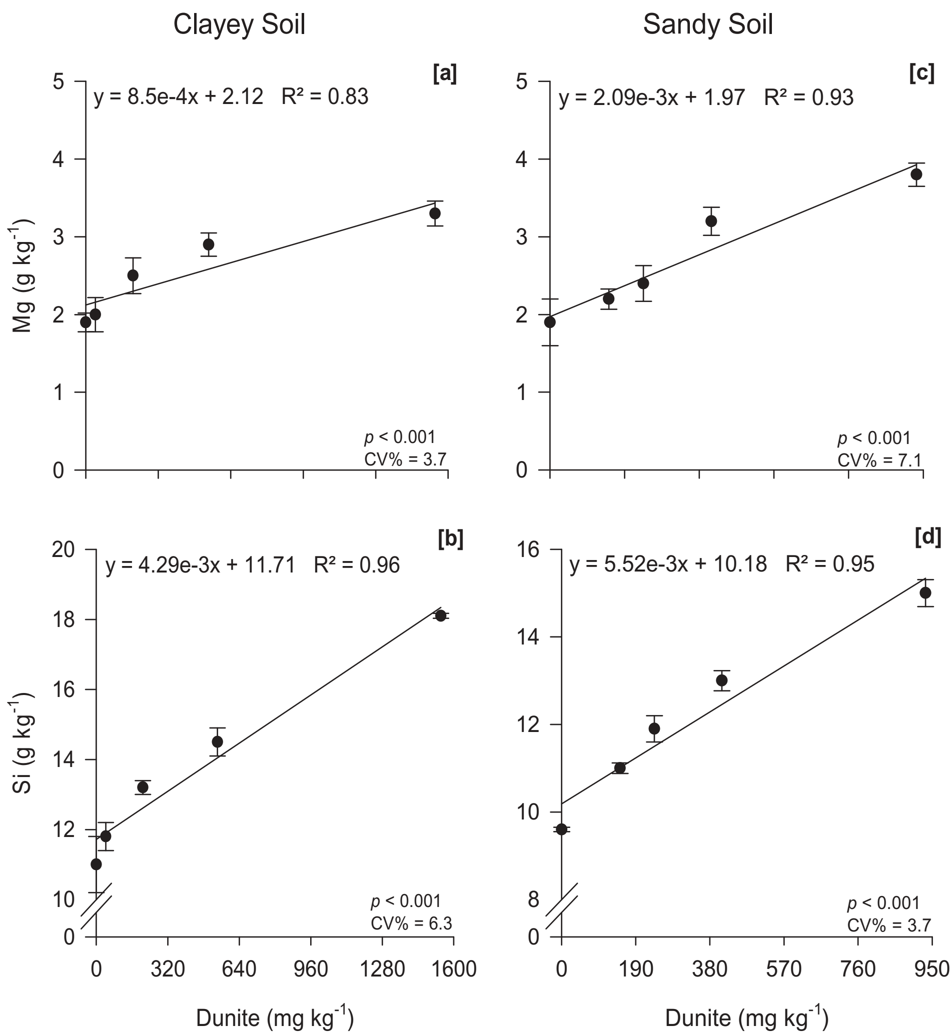


**Figure 1.** Mg (**a**) and Si (**b**) contents in corn leaves grown in clayey soil as a function of the dunite rate. Mg (**c**) and Si (**d**) contents in corn leaves grown in sandy soil as a function of the dunite rate.

In contrast, the efflux transporters (ZmLsi2) are more numerous in the mature root zone (> 10 mm) than in the root tips (Mitani et al. 2009). These efflux transporters are located only in the root endoderm (Ma, Yamaji, and Mitani-Ueno 2011). In the plant, Si is transported in the form of $Si(OH)_4$ silicic acid, and its supply to these types of plants is of paramount importance because it is related to numerous processes of defense against biotic and abiotic factors (Luyckx et al. 2017). Its accumulation in the cell wall has the potential to reduce insect pest attack efficiency and to reduce plant transpiration, especially under conditions of low water availability. In addition to its physical effects, Si participates in the metabolic processes that control salicylic acid, jasmonic and abscissic acid, which are important in the stress-fighting process of plants (Kim et al. 2014).

With the increase in dunite rates, there was a linear increase in reducing sugars and a linear decrease in sucrose and starch contents in the leaves of corn grown in clayey soil (Figure 2). The photosassililated contents at the highest dose of rock powder were 71.4 and 74.8 g kg$^{-1}$ for reducing sugars (Figure 2(a and d)), 42.5 and 42.8 g kg$^{-1}$ for sucrose contents (Figure 2(b and e)) and 43.3 and

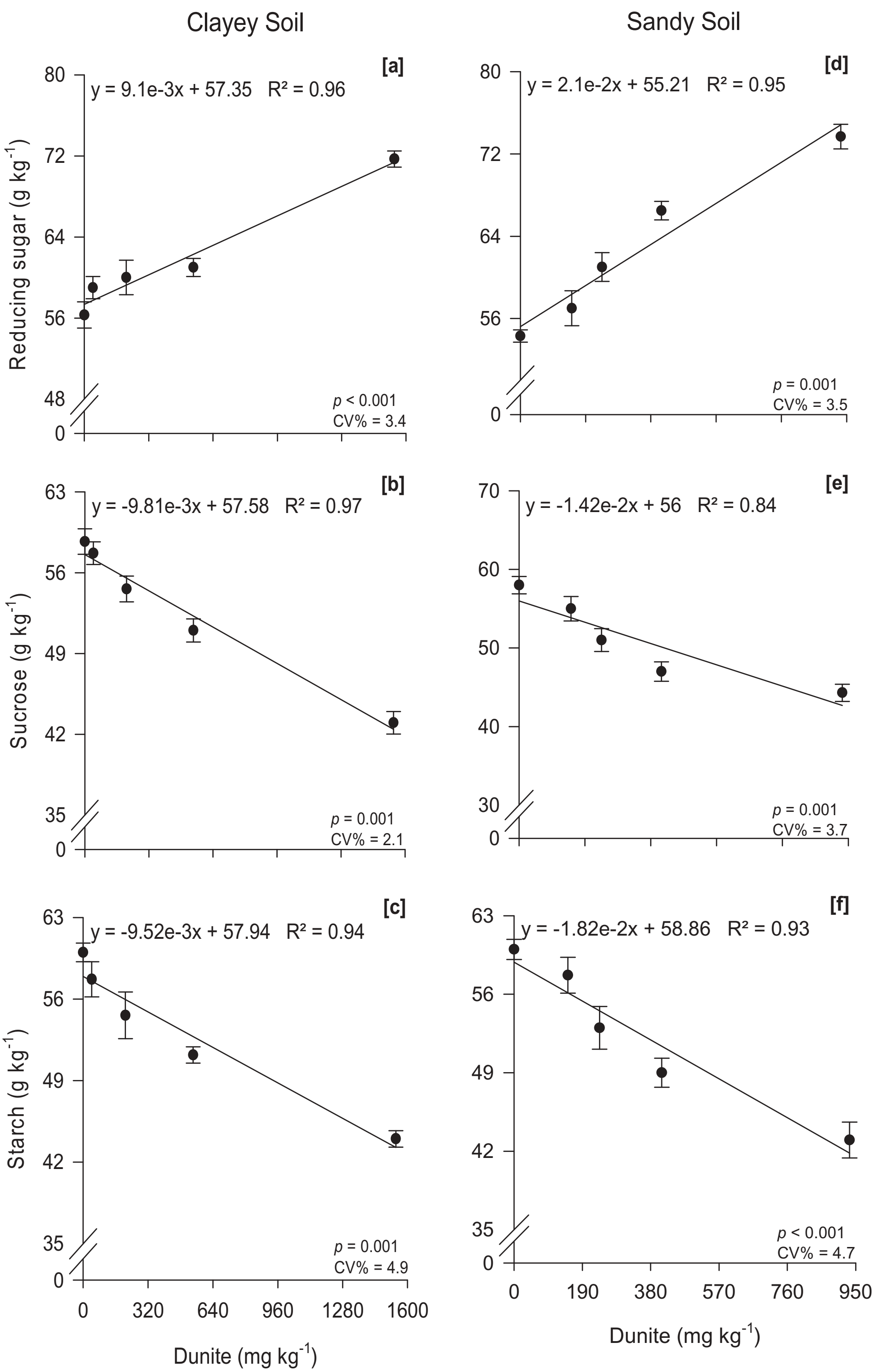


**Figure 2.** Reducing sugars (**a**), sucrose (**b**) and starch (**c**) in dry leaves of corn grown in a clayey soil as a function of the dunite rate. Reducing sugars (**d**), sucrose (**e**) and starch (**f**) in dry leaves of corn grown in a sandy soil as a function of the dunite rate.

41.9 g $kg^{-1}$ for starch contents (Figure 2(c and f)) for corn grown in clayey and sandy soil, respectively. Moretti et al. (2019) reported similar result with the addition of dunite in soybean.

The supply of Mg provided by the solubilization of rock dust strongly influences several processes that modulate the long-distance production and translocation of carbohydrates from the source organs to the plant sink organs (Ceylan et al. 2016; White and Broadley 2009). The production of reducing sugars (fructose + glucose) and their subsequent conversion into sucrose and other more complex carbohydrates are important steps that guarantee plant development. Sucrose is the main form of transport of carbon skeletons in plants and is carried out via the phloem using a proton gradient and an H +/sucrose co-transporter established by a plasma membrane H + -ATPase, which provides energy for the loading process and maintains sucrose transport in phloem cells (Farhat et al. 2016).

The results indicate that the corn plant under increasing doses of dunite, mainly due to the greater availability of Mg, increased the production of reducing sugars, indicating full photosynthetic activity and carbon fixation, whereas decreases in the amount of sucrose indicate that the transport of photoassimilates to the sink organs occurred more efficiently as the levels of rock dust increased. Similarly, the starch formed in the chloroplasts is consumed overnight as the carbon skeleton source for the respiration process, with sucrose as a by-product. This is then transported to the plant sinks and/or is used metabolically (Cakmak and Kirkby 2008; Ceylan et al. 2016).

The corn shoot dry matter (SDM) increased linearly as result of the increase in the dunite rates, regardless of the soil texture, reaching 170 g in the clay soil and 171 g in the sandy textured soil (Figure 3(a and e)). The number of grains per spike showed a quadratic behavior as a function of the increase in the dunite rate in the clayey soil, with a dose of maximum technical efficiency (DMTE) of 981 kg $ha^{-1}$ of rock dust (Figure 3(b)) and a mean of 466 grains per ear, while under cultivation in sandy soil, the averages adjusted to a linear equation increased, with a maximum value of 442 grains per spike (Figure 3(f)). The mass of 100 grains and grain yield per corn plant increased linearly with increasing dunite rates, with respective values of 28.2 g and 154 g $plant^{-1}$ when grown in clay soil (Figure 3(c and d)) and 28.9 g and 153 g $plant^{-1}$ when grown in sandy soil (Figure 3(g and h)).

The biomass accumulation of corn plants presented the same trend as the nutritional and photosynthetic metabolism. Cell division and expansion depend directly on the full metabolic functioning of the plant, which is influenced by photosynthetic nutrition and performance. All processes governing photosynthesis, the activation of enzymes linked to carbon fixation, and partitioning of photoassimilates are strongly modulated by the Mg supply (Ceylan et al. 2016). In this way, energy conversion occurs in SDM accumulation and grain filling. The direct translocation of photoassimilates and the redistribution of the reserve pool to the drainage organs contribute to grain filling (Ceylan et al. 2016). The reserve tissue of cereal grains is amyliferous; thus, the poor translocation of carbohydrates to grains implies a reduction in the final weight (Wang et al. 2012). Si may also have contributed to the results obtained. Si is a strong agent in the composition of the cell wall, providing mechanical support to the plant structures (Ma et al. 2007). Its supply guarantees better leaf architecture, favoring light interception, and contributing to greater photosynthetic activity (Haynes 2017).

The application of the dunite altered some soil chemical attributes, increasing the pH of the clayey soil after corn cultivation, raising the pH to 5.6 at the highest dose of rock dust (Figure 4(a)), whereas when applied to sandy soil, the response was quadratic for this same attribute, with DMTE of 785 kg $ha^{-1}$ and a pH value of 5.5 (Figure 4(b)). In the same way that the Mg and Si contents increased linearly by increasing the dose of rock dust, the content of these elements increased linearly in the soil. The respective contents of Mg and Si at the highest dunite rate were 24.1 $mmol_c$ $dm^{-3}$ and 21.31 mg $dm^{-3}$ in the clayey soil (Figure 4(b and c)) and 9.7 $mmol_c$ $dm^{-3}$ and 10.3 mg $dm^{-3}$ in the sandy soil (Figure 4(e and f)).

Dunite is composed of magnesium silicate, a neutralizing species capable of reducing the active acidity of the soil. The rock powder consists of 34% $SiO_2$ and 40% MgO, both with a neutralization capacity relative to $CaCO_3$ of 1.0 and 2.5 times, respectively (Alcarde 2005). This material is another

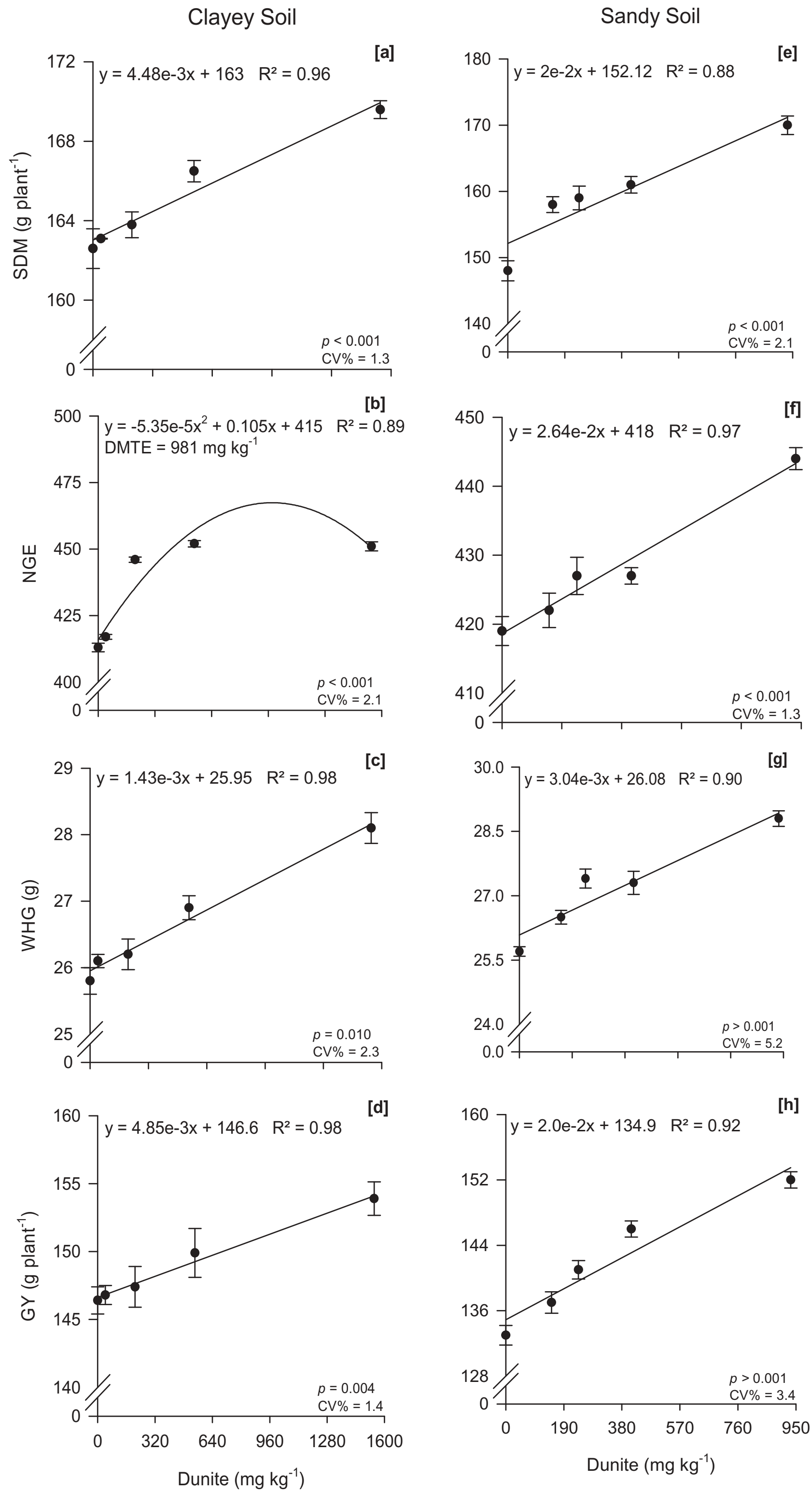


**Figure 3.** Shoot dry matter – SDM (**a**), number of grains per ear – NGE (**b**), weight of 100 grains – WHG (**c**) and grain yield – GY (**d**) as a function of the dunite rate in clayey soil. SDM **(e)**, NGE **(f)** WHG **(g)** and GY **(h)** as a function of the dunite rate in sandy soil.

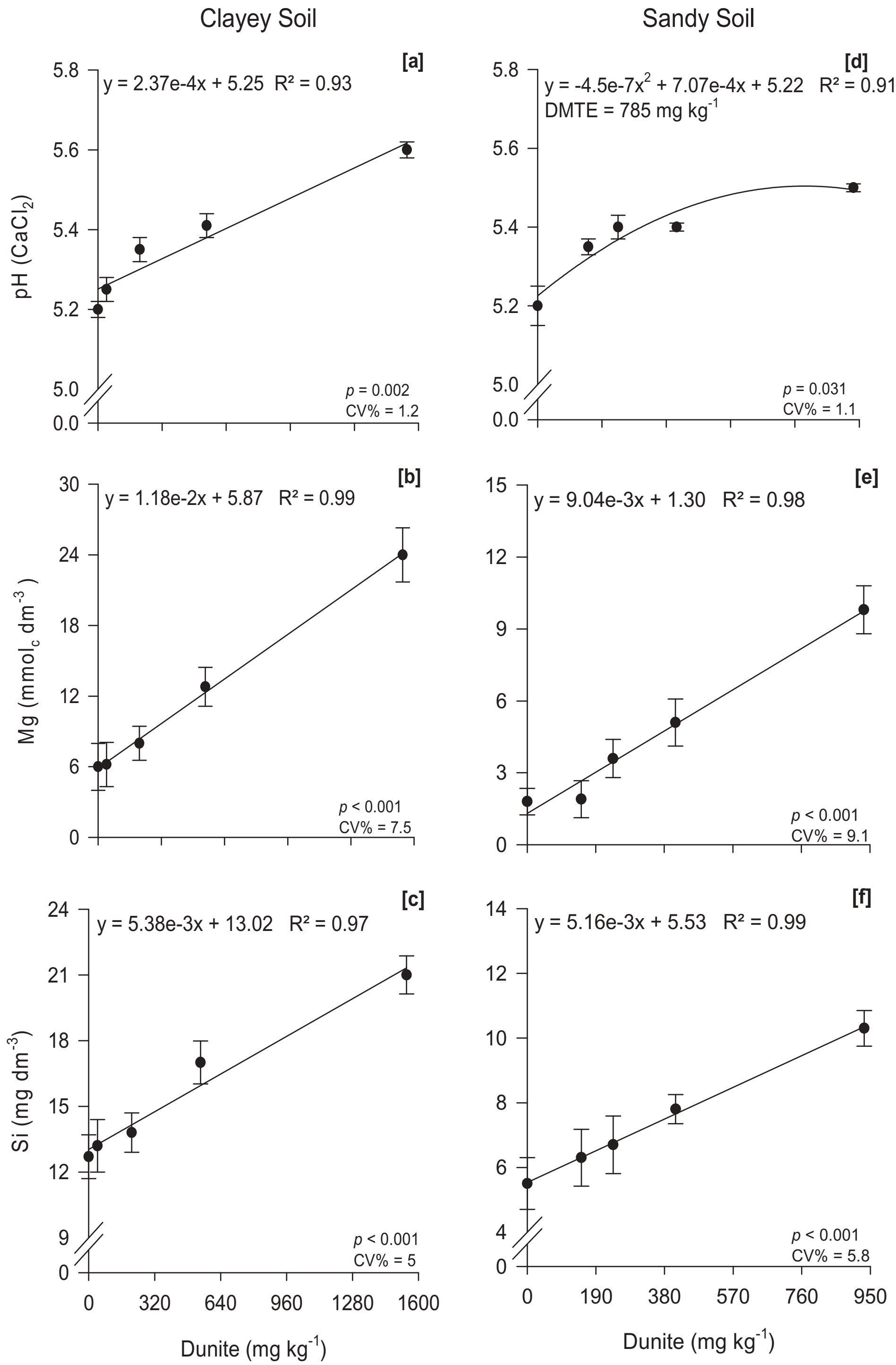


**Figure 4.** pH (**a**), Mg (**b**) and Si (**c**) contents in clayey soil after corn cultivation under different dunite rates. pH (**d**), Mg **(e)** and Si (**f**) contents in sandy soil after corn cultivation under different dunite rates.

important source of soil acidity correction, in addition to providing Mg and Si to the system (Castro and Crusciol 2013).

The levels of these soil elements increased in the same proportion as the dunite levels used. It is of great importance to emphasize that the texture of the soil directly influences the changes in pH depending on the dose. Soil sandy soils have a relatively low buffering power (Barbosa et al. 2008), which explains the absence of responses to the higher Dunite rates in this type of soil, while in the clay soil, the pH change response was linear with an increase in the dunite rates. As for the Mg and Si contents obtained in the two soil types, it is evident that the clayey soil naturally has a higher capacity of cation retention in its colloids. In contrast, the values found in the sandy soil did not limit the development of the crop, presenting data similar to those obtained when corn was grown in the clay soil. This fact indicates that the process of serpentinization that occurs during dunite processing is highly efficient and is able to make these nutrients available in less fertile soils.

In general, it is necessary that the minerals present in the rock powder be weathered to become available in the soil and absorbed by the plants, a fact that is potentially greater in soils with a more clayey texture. More clayey soils present higher water retention capacity, soil organic matter and, consequently, higher soil microbiological activity, which are highly connected with the intemperization of soil minerals (Silva et al. 2012). Thus, sandy soils would be less prone to successful application of rock dust products. However, in the present study, the dunite was not limiting in the soil with a sandy texture and was able to supply the plants with Mg and Si.

## Conclusions

Rock dust technology is a mechanism of remineralization of soils for a sustainable tropical agriculture. There was an increase in the Mg and Si contents in the plant and soil and acidity correction (pH) with the application of dunite to clayey and sandy soils. The increased rates resulted in a higher content of reducing sugars and lower levels of sucrose and foliar starch and thus better partitioning of metabolites for the corn crop. Dunite resulted in greater vegetative growth, filling and yield of corn kernels in soil with a clayey and sandy texture.

## Acknowledgments

The National Council for Scientific and Technological Development (CNPq) for an award for excellence in research of the first and fourth authors.

## ORCID

C. A. C. Crusciol http://orcid.org/0000-0003-4673-1071

## References

Alcarde, J. C. 2005. *Soil acidity correctives: characteristics and technical interpretations [Corretivos da acidez dos solos: características e interpretações técnicas]*, 24. São Paulo: ANDA.

Assis, L. G., and F. M. Dias. 2007. *Study of the viability of the dunite rock from Catas Altas-MG as an aggregate for concrete [Estudo da viabilidade da utilização da rocha dunito, proveniente de Catas Altas-MG, como agregado para concreto]*. Resende, Brazil: IV SEGeT.

Barbosa, N. C., R. Venâncio, M. H. S. Assis, J. D. B. Paiva, M. A. C. Carneiro, and H. S. Pereira. 2008. Forms of application of calcium and magnesium silicate in sorghum crop in a savannah quartzipsamment soil. *Pesquisa Agropecuária Tropical* 38:290–96. doi:10.5216/pat.v38i4.3861.

Cakmak, I., and E. A. Kirkby. 2008. Role of magnesium in carbon partitioning and alleviating photoxidative damage. *Physiologia Plantarum* 133:692–704. doi:10.1111/j.1399-3054.2007.01042.x.

Canizella, B. T., J. A. Souza, A. Moreira, and L. A. C. Moraes. 2018. Magnesium and zinc interaction in four soybean cultivars with different nutritional requirements. *Journal of Plant Nutrition* 41:2189–99. doi:10.1080/01904167.2018.1485934.

Castro, G. S. A., and C. A. C. Crusciol. 2013. Effects of superficial liming and silicate application on soil fertility and crop yield under rotation. *Geoderma* 195:234–42. doi:10.1016/j.geoderma.2012.12.006.
Ceylan, Y., U. B. Kutman, M. Mengutay, and I. Cakmak. 2016. Magnesium applications to growth medium and foliage affect the starch distribution, increase the grain size and improve the seed germination in wheat. *Plant and Soil* 406:145–56. doi:10.1007/s11104-016-2871-8.
Chiba, Y., N. Mitani, N. Yamaji, and J. F. Ma. 2009. HvLsi1 is a silicon influx transporter in barley. *The Plant Journal* 57:810–18. doi:10.1111/j.1365-313X.2008.03728.x.
CONAB (National Supply Company). 2019. *Historical series of crops* [Série histórica das safras]. Accessed July 23, 2019. https://www.conab.gov.br/info-agro/safras/serie-historica-das-safras>.
Crusciol, C. A., A. C. Artigiani, O. Arf, A. C. Carmeis Filho, R. P. Soratto, A. S. Nascente, and R. C. Alvarez. 2016. Soil fertility, plant nutrition, and grain yield of upland rice affected by surface application of lime, silicate, and phosphogypsum in a tropical no-till system. *Catena* 137:87–99. doi:10.1016/j.catena.2015.09.009.
Farhat, N., A. Elkhouni, W. Zorrig, A. Smaoui, C. Abdelly, and M. Rabhi. 2016. Effects of magnesium deficiency on photosynthesis and carbohydrate partitioning. *Acta Physiologiae Plantarum* 38:3–10. doi:10.1007/s11738-016-2165-z.
Fernandes, F. R. C., A. B. D. Luz, and Z. C. Castilhos. 2010. *Agrominerals for Brazil [Agrominerais para o Brasil]*. Rio de Janeiro, Brazil: CETEM/MCT.
Haynes, R. J. 2017. Significance and role of Si in crop production. *Advances in Agronomy* 146:83–166. doi:10.1016/bs.agron.2017.06.001.
Institute, S. A. S. 2015. *Procedure guide for personal computers*. Version 9.4. Cary, NC: SAS Inst..
Kim, Y. H., A. L. Khan, D. H. Kim, S. Y. Lee, K. M. Kim, M. Waqas, H. Y. Jung, J. H. Shin, J. G. Kim, and I. J. Lee. 2014. Silicon mitigates heavy metal stress by regulating P-type heavy metal ATPases, Oryza sativa low silicon genes, and endogenous phytohormones. *BMC Plant Biology* 14:13. doi:10.1186/1471-2229-14-13.
Kwano, B. H., A. Moreira, L. A. C. Moraes, and M. A. Nogueira. 2017. Magnesium-manganese interaction in soybean cultivars with different nutritional requirements. *Journal of Plant Nutrition* 40:372–81. doi:10.1080/01904167.2016.1240198.
Luyckx, M., J. F. Hausman, S. Lutts, and G. Guerriero. 2017. Silicon and plants: Current knowledge and technological perspectives. *Frontiers in Plant Science* 8:411. doi:10.3389/fpls.2017.00411.
Ma, J. F., N. Yamaji, N. Mitani, K. Tamai, S. Konishi, T. Fujiwara, M. Katsuhara, and M. Yano. 2007. An efflux transporter of silicon in rice. *Nature* 448:209–12. doi:10.1038/nature05964.
Ma, J. F., N. Yamaji, and N. Mitani-Ueno 2011. Transport of silicon from roots to panicles in plants. *Proceedings of the Japan Academy,* Tokyo, Japan 87:377–85. doi:10.2183/pjab.87.377
Malavolta, E., G. C. Vitti, and S. A. Oliveira. 1997. *Evaluation of Nutritional Status of Plants; principles and applications [Avaliação do estado nutricional das plantas: princípios e aplicações]*. Piracicaba, Brazil: Associação Brasileira para Pesquisa da Potassa e do Fosfato.
Mitani, N., Y. Chiba, N. Yamaji, and J. F. Ma. 2009. Identification and characterization of maize and barley Lsi2-like silicon efflux transporters reveals a distinct silicon uptake system from that in rice. *The Plant Cell* 21:2133–42. doi:10.1105/tpc.109.067884.
Moreira, A., C. Castro, F. A. Oliveira, L. H. Salinet, and C. O. Veronesi. 2006. Potencial de uso de rochas brasileiras como fertilizantes e corretivos da acidez do solo. *Espaço & Geografia* 9:47–61.
Moretti, L. G., J. W. Bossolani, C. A. C. Crusciol, A. Moreira, P. H. Micheri, R. Rossi, and C. Imaizumi. 2019. Dunite in Agriculture: physiological changes, nutritional status and soybean yield. *Communications in Soil Science and Plant Analysis* 50:1–10. doi:10.1080/00103624.2019.1635143.
Nelson, N. 1944. A photometric adaptation of the Somogyi method for the determination of glucose. *The Journal of Biological Chemistry* 153:375–80.
Nikolic, M., N. Nikolic, Y. Liang, E. A. Kirkby, and V. Römheld. 2007. Germanium-68 as an adequate tracer for silicon transport in plants. Characterization of silicon uptake in different crop species. *Plant Physiology* 143:495–03. doi:10.1104/pp.106.090845.
Raij, B., J. C. Andrade, H. Cantarella, and J. A. Quaggio. 2001. *Chemical analysis for fertility evaluation of tropical soils [Análise química para avaliação da fertilidade de solos tropicais]*. Campinas, Brazil: Instituto Agronômico.
Ramos, C. G., X. Querol, A. C. Dalmora, K. C. Jesus Pires, I. A. H. Schneider, L. F. S. Oliveira, and R. M. Kautzmann. 2017. Evaluation of the potential of volcanic rock waste from southern Brazil as a natural soil fertilizer. *Journal of Cleaner Production* 142:2700–06. doi:10.1016/j.jclepro.2016.11.006.
Ramos, C. G., X. Querol, M. L. Oliveira, K. Pires, R. M. Kautzmann, and L. F. Oliveira. 2015. A preliminary evaluation of volcanic rock powder for application in agriculture as soil a remineralizer. *Science of the Total Environment* 512:371–80. doi:10.1016/j.scitotenv.2014.12.070.
Santos, H. G., P. K. T. Jacomine, L. H. C. Anjos, V. A. Oliveira, J. F. Lubreras, M. R. Coelho, J. A. Almeida, T. J. F. Cunha, and J. B. Oliveira. 2013. *Brazilian System of Soil Classification [Sistema brasileiro de classificação de solos]*. Brasília, Brazil: Embrapa.
Shapiro, S. S., and M. B. Wilk. 1965. An analysis of variance test for normality (complete samples). *Biometrika* 52:591–11. doi:10.1093/biomet/52.3-4.591.

Silva, A., J. A. Almeida, C. Schmitt, and C. M. M. Coelho. 2012. Evaluation of application of basalt powder effects in soil fertility and *Eucalyptus benthamii* nutrition. *Floresta* 42:69–76. doi:10.5380/rf.v42i1.26300.

Tränkner, M., E. Tavakol, and B. Jákli. 2018. Functioning of potassium and magnesium in photosynthesis, photosynthate translocation and photoprotection. *Physiologia Plantarum* 163:414–31. doi:10.1111/ppl.12747.

Wang, X., J. Cai, F. Liu, M. Jin, H. Yu, D. Jiang, B. Wollenweber, T. Dai, and W. Cao. 2012. Pre-anthesis high temperature acclimation alleviates the negative effects of post-anthesis heat stress on stem stored carbohydrates remobilization and grain starch accumulation in wheat. *Journal of Cereal Science* 55:331–36. doi:10.1016/j.jcs.2012.01.004.

White, P. J., and M. R. Broadley. 2009. Biofortification of crops with seven mineral elements often lacking in human diets–iron, zinc, copper, calcium, magnesium, selenium and iodine. *New Physiologist* 182:49–84. doi:10.1111/j.1469-8137.2008.02738.x.