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Dunite in Agriculture: Physiological Changes, Nutritional Status and Soybean Yield

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ABSTRACT

Brazil is an importer of fertilizers and the use of alternative sources is increasing in 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 soybean yield [*Glycine max* (L.) Merril] in two soil types. The treatments consisted in the 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 Mg and Si contents, reducing sugars and foliar glucose, as well as pH, Mg and Si of the soil, and yield components showed a positive response due to the increase of input rates. The Mg nutrition provides lower foliar starch levels, consequently, the best partition of metabolites to plant leads to better development, filling and yield of soybeans.

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KEYWORDS
Glycine max; magnesium fertilization; metabolites; silicium

Introduction

The ability of soils to produce the food needed to support a global population expected to exceed 9.0 billion by 2050 is fundamental to sustainable development (Keesstra et al. 2016). In this sense, the soybean [*Glycine max* (L.) Merril] crop plays an essential role as one of the most important 'commodities' in Brazil, accounting for approximately 13% of all exports in the country (Moretti et al. 2018). Soil fertility management and crop fertilization are determinant for higher economic yields, and vary for each region, according to each production system (TPS 2013).

Rock dust technology is a mechanism of remineralization of soils for a sustainable tropical agriculture. Replacing the use of chemical fertilizers used in monoculture of large scale, with environmental and economic gains, this technology that has been developed in Brazil and allows restoring the food and economic sovereignty of agricultural countries that are heavily dependent on the import of chemical inputs (Moreira et al. 2006; Theodoro et al. 2012).

In this sense, several efforts have been made in recent years to mitigate the different environmental impacts related to agricultural activities. In particular, the use of conventional synthetic fertilizers, draw significant attention due to the adverse environmental impacts caused by the excessive application of these products (Nunes, Kautzmann, and Oliveira 2014; Ramos, Mello, and Kautzmann 2014). According to Ramos et al. (2015), given that Brazil is one of the largest suppliers of food in the world, the 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 the mining activity and food production.

The volcanic rock dust is composed mainly of SiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, Na_2O, K_2O, and CaO (Nunes, Kautzmann, and Oliveira 2014; Ramos, Mello, and Kautzmann 2014; Ramos et al. 2015).

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According to Assis and Dias (2007), Dunite is an igneous rock, which is essentially a peridotite, magmatic or eruptive, consisting mostly of olivine $(MgFe)_2SiO_4$, containing approximately 40% of Mg oxide (MgO) and 34% of 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 in order to improve the conditions of soil fertility (Ramos et al. 2017).

Thus, this study aimed to evaluate the effect of fertilization with Dunite on the nutritional, metabolic and grain yield of soybean, as well as on the soil chemical attributes in two soils with different clay content.

Materials and methods

A greenhouse experiment carried out in the 2016/2017 cropping season at College of Agricultural Science, Department of Crop Science, Botucatu County, São Paulo State, Brazil. The soils used in the experiment were two Rhodic Hapludox (Santos et al. 2013) with a clayey and sandy texture, respectively. The clayey soil contained 602 g kg^{-1} clay and 281 g kg^{-1} sand and the sandy soil 259 g kg^{-1} clay and 724 g kg^{-1} of sand.

The soil chemical attributes (0.0–0.2 m) were determined according to van Raij et al. (2001). Clay soil – soil organic matter (SOM) 25.2 g dm^{-3}; pH in $CaCl_2$ 5.2; phosphorus (P_{resin}) 6.0 mg dm^{-3}, potassium (K^+) 0.7 $mmol_c$ dm^{-3}, calcium (Ca^{2+}) 35.0 $mmol_c$ dm^{-3}, Mg^{2+} 8.0 $mmol_c$ dm^{-3}, potential acidity (H^++Al^{3+}) 29.0 $mmol_c$ dm^{-3}, aluminum (Al^{3+}) 0.0 $mmol_c$ dm^{-3}, cation-exchange capacity (CEC) 73.0 $mmol_c$ dm^{-3}, iron (Fe) 20.0 mg dm^{-3}, copper (Cu) 8.4 mg dm^{-3}, manganese (Mn) 15.3 mg dm^{-3}, zinc (Zn) 0.9 mg dm^{-3}, and boron (B) 0.4 mg dm^{-3} and sandy soil – SOM 13.1 g dm^{-3}, pH in $CaCl_2$ 5.4; P_{resin} 3.0 mg dm^{-3}, K^+ 0.5 $mmol_c$ dm^{-3}, Ca^{2+} 18.0 $mmol_c$ dm^{-3}, Mg^{2+} 2.0 $mmol_c$ dm^{-3}, H^++Al^{3+} 18.0 $mmol_c$ dm^{-3}, Al^{3+} 0.0 $mmol_c$ dm^{-3}, CEC 38.0 $mmol_c$ dm^{-3}, Fe 35.0 mg dm^{-3}, Cu 1.6 mg dm^{-3}, Mn 1.9 mg dm^{-3}, Zn 0.3 mg dm^{-3}, and B 0.3 mg dm^{-3}.

Dunite presents the following chemical characteristics: 24% Mg (40% MgO) and 16% Si (34% SiO_2). The experimental design was completely randomized, composed of four Dunite rates and an absolute control, with four replicates, for both soils. The treatments consisted in the application of five Dunite rates: 0, 42, 208, 542 and 1542 mg kg^{-1} for clayey soils, and five Dunite rates: 0, 150, 238, 411, and 933 mg kg^{-1} for sandy soil. Pots with 15 L of capacity were used in two experiments.

Nutrients were supplied as 200 mg *P* kg^{-1}, 150 mg K kg^{-1}, 15.0 mg S kg^{-1}, 5 mg Zn kg^{-1}, 1.5 mg B kg^{-1}, and 0.5 mg Cu kg^{-1}. Phytosanitary treatments were carried out according to the recommendation for the soybean crop (TPS 2013). Soil water content in pots was corrected to −0.01 MPa (field capacity), corresponding to 112 g kg^{-1}, respecting the equilibration period (60–100% field capacity). Five seeds (cultivar TMG 7062 RR) were sown per treatment, and three plants were left per pot after the 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).

In the soybean R_2 growth stage (Fehr et al. 1971), leaves were collected and ground in a Wiley-type mill coupled to a 1.0 mm sieve to then determine the content Mg and Si (Malavolta, Vitti, and Oliveira 1997). The partitioning of carbohydrates by reducing sugars (glucose and fructose), sucrose and starch content, obtained in the dry matter of leaves, was determinate according to the methodology described by Nelson (1994).

At the same time of the foliar diagnosis, two plants were collected for analysis. The remaining plant was conducted until the end of the cycle, and from it the mass of 100 grains was determined by means of a precision scale weighing and value correction (13% on a wet basis). The grain yield was expressed as g $plant^{-1}$. After harvest, a soil sample of each pot was collected and analyzed the content of pH, Mg, and Si, according to a methodology of van Raij et al. (2001).

Data from each experiment were first submitted to tests of normality and homogeneity of variances for each variable. The data were submitted to the analysis of variance (ANOVA) and F test ($p \leq 0.05$). Treatment means were compared by the polynomial regression, also at $p \leq 0.05$.

Results and discussion

The increase of Dunite rates in soybean cultivation in both soil types increased the Mg and Si leaf contents linearly (Figure 1a–d). The leaf contents obtained from these elements at the highest rate of the product were of 5.3 and 5.4 g kg^{-1}, respectively (Figure 1a,b) in the clayey soil culture and 5.2 and 5.6 g kg^{-1} (Figure 1c,d) in the sandy soil. By passing through the serpentinization procedure, whereby more than 90% of Mg and Si of Dunite undergo temperature variations below 400°C, a hydration of these minerals occurs, making them more soluble in the system and susceptible for uptake by plants (Fernandes, Luz, and Castilhos 2010). As for Mg, it is important to emphasize the importance of this nutrient in productive systems, given its functions for plant growth and development (Gransee and Führs 2013), as well as its relation to a great number of key functions in plants (Cakmak and Yazici 2010; Canizella et al. 2015). Besides being a main component of the chlorophyll molecule, much of the non-structural Mg is involved in the activation of enzymes, such as rubisco, in the photosynthetic process, in the supply of adenosine triphosphate (ATP) as an energy source and

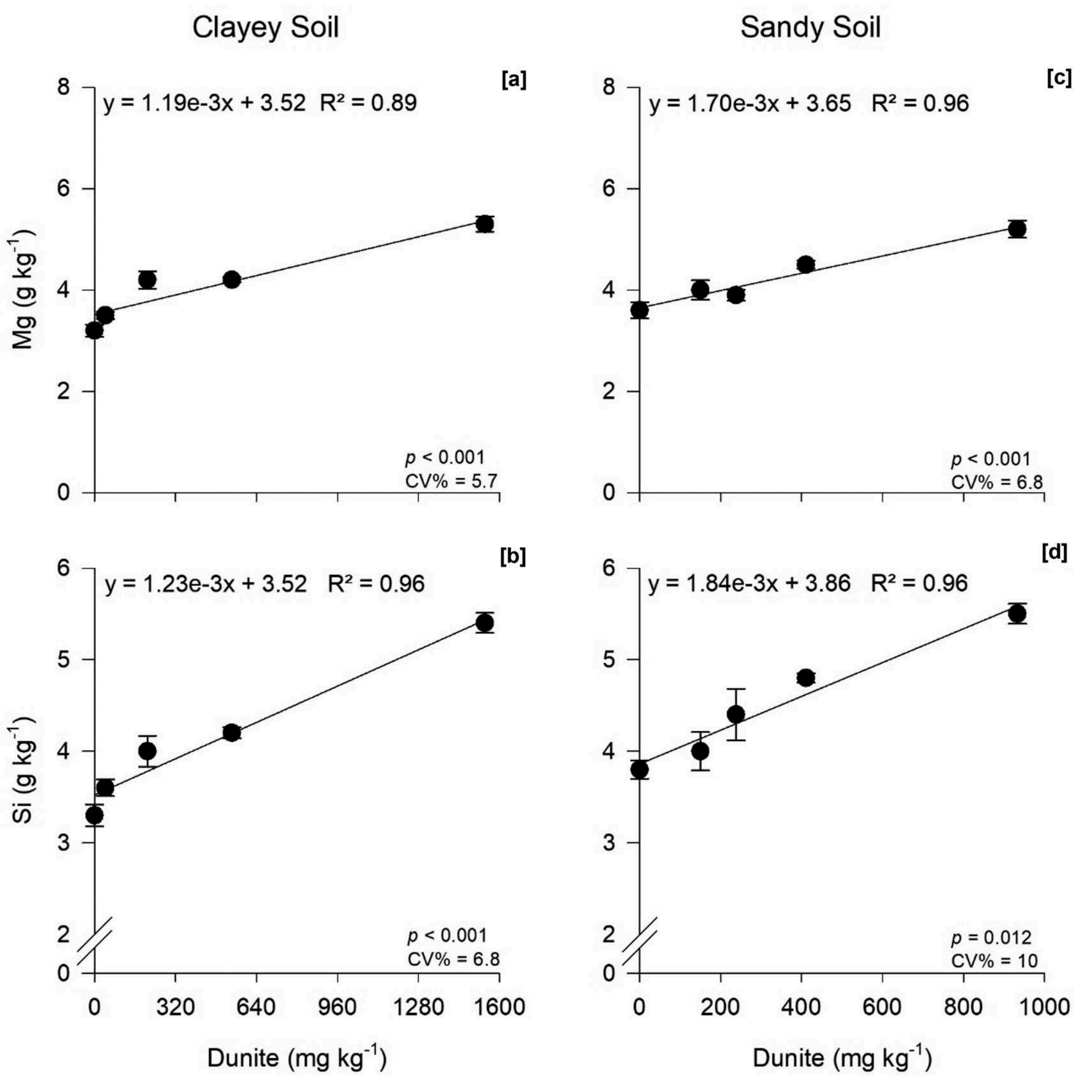

Figure 1. Mg content (a) and Si (b) in soybean leaves grown in clayey soil as a function of Dunite rates. Mg content (c) and Si (d) in soybean leaves grown in sandy soil as a function of Dunite rates.

in the transport of photosynthates from source organs to sink organs (Cakmak and Kirkby 2008; Ceylan et al. 2016; Kwano et al. 2017).

The Si supply, although not considered an essential element, has a secondary importance in several processes, working as a stress relief of biotic and abiotic origin due to the formation of a silica layer on the cell wall (Luyckx et al. 2017), besides having roles in the balance of phytohormones, reducing the endogenous concentration of jasmonic acid (JA) and salicylic acid (SA) and increasing the abscisic acid (ABA) in situations of stressors (Kim et al. 2014). The soybean is as an intermediate plant in terms of Si accumulation in the plant tissue; however, the content of this element, in the form of silicic acid [$Si(OH)_4$], can reach relevant levels, demonstrating that there is an active transport of this element from the roots (Mitani and Ma 2005) by aquaporin channels (Ma et al. 2007).

The carbohydrate metabolism of soybean plants was significantly influenced by the use of Dunite rates, regardless of the soil in which it was cultivated (Figure 2a–f). The leaf contents of reducing sugars and sucrose increased linearly with the increase of rates, reaching values of 68.7 and 58.6 g kg^{-1} (Figure 2a,b) for cultivation in clayey soil and 78.9 and 74.5 g kg^{-1} (Figure 2d,e) in the sandy soil. The starch contents of source leaves were reduced by the use of larger Dunite rates (Figure 2c,f).

Mg is an element that is highly supplied by the solubilization of rock dust (Moreira et al. 2006; Theodoro and Leonardos 2006), acts on several processes that modulate the production and translocation of carbohydrates in plants (Ceylan et al. 2016), and activates almost all phosphorylative enzymes that form bridges between adenosine triphosphate (ATP) and adenosine diphosphate (ADP) (Kwano et al. 2017). The transport of carbohydrates over long distances, such as reducing sugars (fructose + glucose) and sucrose, is carried out by the phloem and is strongly affected by the Mg availability (Farhat et al. 2016). The sucrose on the phloem is an active process catalyzed by a proton gradient and H^+/sucrose co-transporter, established by H^+-ATPase located on the plasma membrane (Ward, Lamb, and Fehon 1998). For its proper functioning, the existence of Mg-ATP (Igamberdiev and Kleczkowski 2003) is essential, and for that, an additional Mg is needed. Moreover, the increase in Mg supply may have provided improvements in the H^+-ATPase activity of the phloem cells, increasing the sucrose concentration for export by triose-*P*, not allowing its accumulation in the chloroplast of leaves. As a consequence, the enzyme ADP-glucose pyrophosphorylase (AGPase) is not activated and there is no accumulation of starch in the chloroplasts (Sonnewald 2001), demonstrating that the translocation of carbon skeletons to the plant sinks happens efficiently due to the greater Mg availability (Ceylan et al. 2016; Farhat et al. 2016).

The phytotechnical and productive components of the soybean crop increased linearly by using higher Dunite rates in both soils (Figure 3a–f). The accumulation of dry weight in the shoot area, mass of 100 grains and yield of soybean grains per plant presented values of 19.9 g plant^{-1}, 18.7 g and 19.4 g, respectively (Figure 3a–c) for soybean cultivation in clayey soil and 19.4 g plant^{-1}, 17.6 g and 17.6 g (Figure 3d–f) on sandy soil.

The metabolism of carbohydrates and their partitioning among plant organs are factors that determine the productive potential of the crops. The benefits evidenced in this work on the dynamics of the production and destination of the photosynthates provided a greater contribution of dry weight in the soybean crop, besides increasing the grain mass and, consequently, the grain yield per plant. During the vegetative phase, the photoassimilates are converted into plant growth, especially if there is no nutritional limitation (Tränkner, Tavakol, and Jákli 2018). During grain filling (reproductive period of culture), sugars from photosynthesis are directed to the reproductive organs. The number of fertilized ovules and the final grain weight are determined by the rate of transport and assimilation during this period and also by the duration of the grain filling (Yang and Zhang 2005). Both the direct translocation of assimilates and the redistribution of the reserve pool of assimilates contribute to better indices of these variables (Tränkner, Tavakol, and Jákli 2018). This way, the reduction of the translocation of carbohydrates to grains, mainly under Mg deficiency, directly affects the productive potential of the crops (Ceylan et al. 2016; Farhat et al. 2016). The Dunite, regardless of the soil in which it was used, provided adequate nutrition to the soybean crop, especially by supplying Mg, as well as Si, an element through which innumerable plant defense

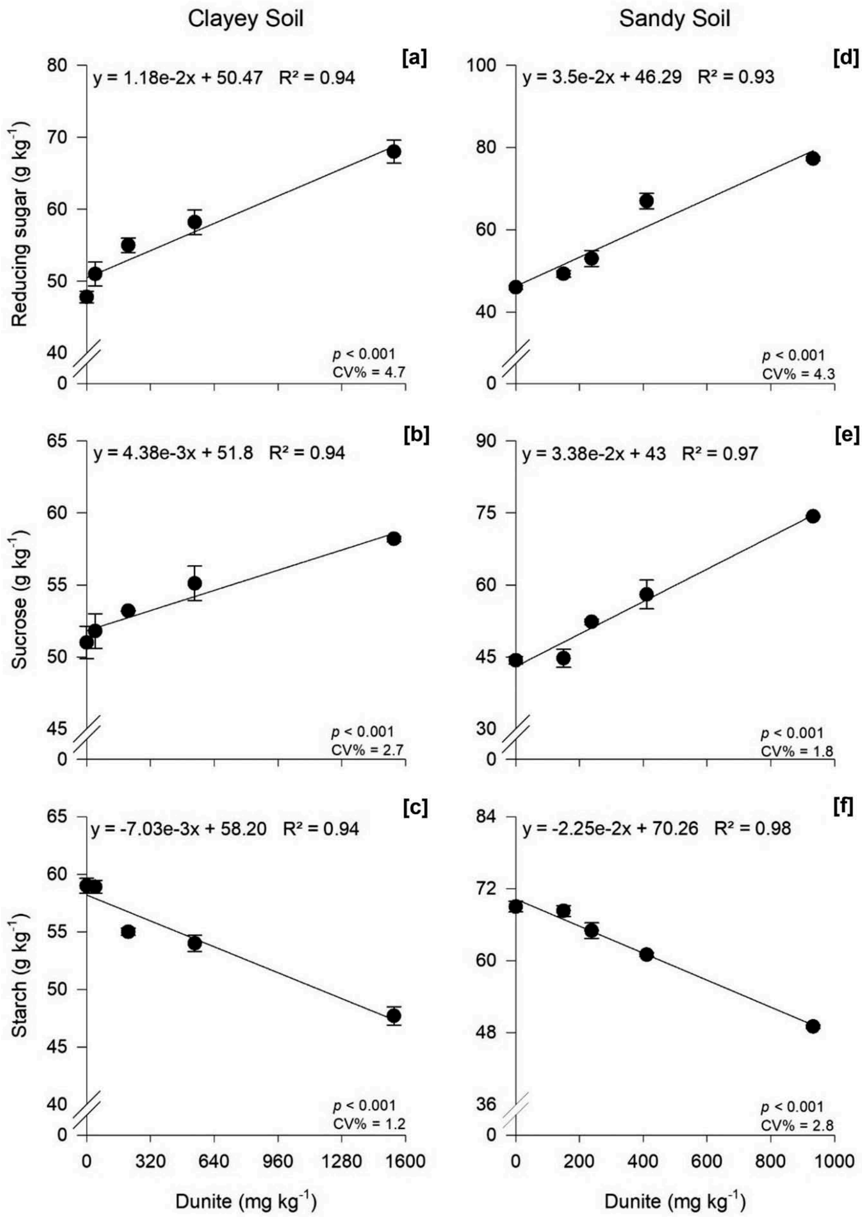

Figure 2. Reducing sugars (a), sucrose (b) and starch (c) in dry weight of soybean leaves grown in a clayey soil as a function of Dunite rates. Reducing sugars (a), sucrose (b) and starch (c) in dry weight of soybean leaves grown in sandy soil as a function of Dunite rates.

processes (physical barriers, improved plant architecture and antioxidant metabolism) are activated (Haynes 2017; Luyckx et al. 2017).

Significant changes in soil chemical attributes were also obtained by the use of Dunite rates in clayey and sandy soils (Figure 4a–f). The pH of the clayey soil increased linearly until reaching the value of 5.3 (Figure 4a), while for the sandy soil, the means obtained were adjusted to a quadratic equation, obtaining a rate of maximum technical efficiency (DMTE) of 636 g kg^{-1} of soil and a maximum pH value of 5.5 (Figure 4d). Mg and Si contents of the soil followed the same tendency

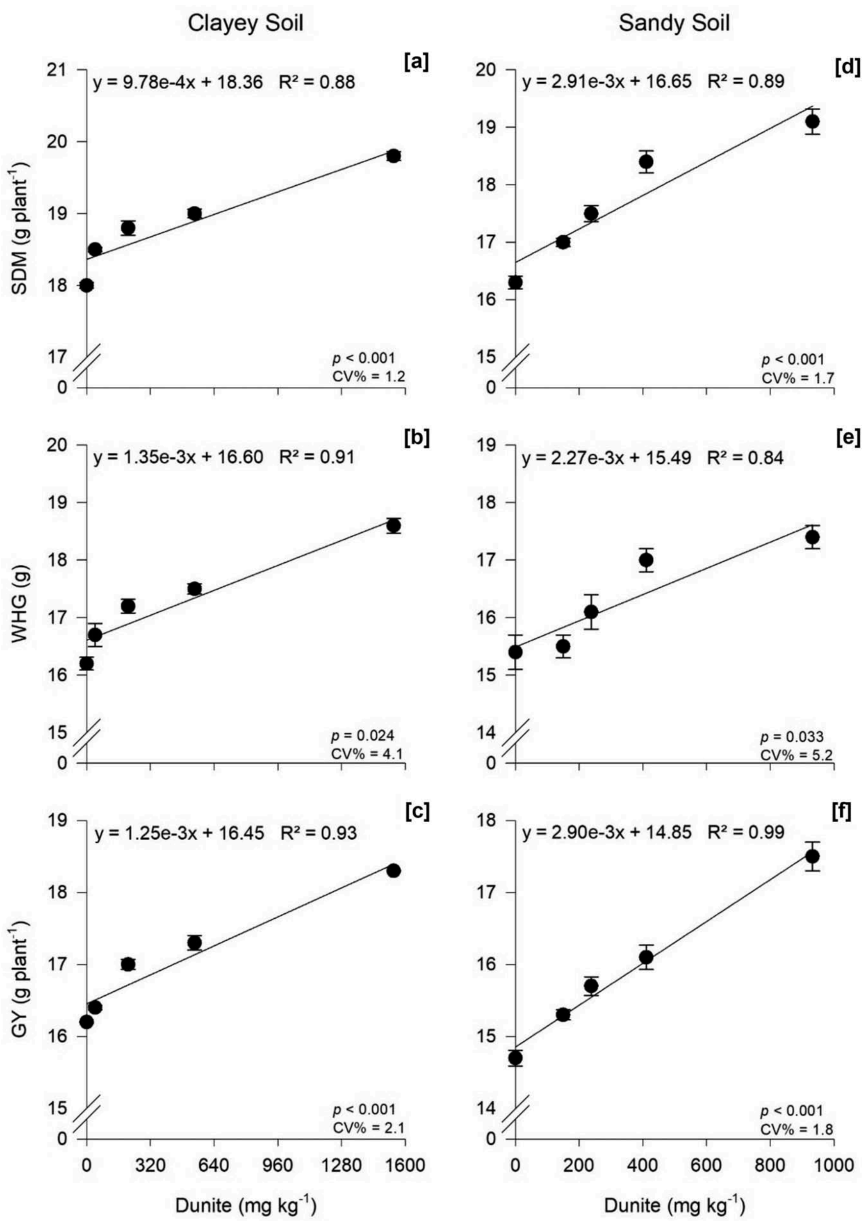

Figure 3. Shoot dry weight – SDM (a), weight of 100 grains – WHG (b) and grain yield – GY (c) in clayey soil as a function of Dunite rates. Shoot dry weight – SDM (d), weight of 100 grains – WHG (e) and grain yield – GY (f) in sandy soil as a function of Dunite rates.

obtained for the leaf, which increased linearly with the increase of Dunite rates. The values obtained of Mg and Si were 22.9 $mmol_c\ dm^{-3}$ and 22.4 $mg\ dm^{-3}$ in the clayey soil (Figure 4b,c), and 9.2 $mmol_c\ dm^{-3}$ and 10.5 $mg\ dm^{-3}$ in the sandy soil (Figure 4e,f), respectively.

The soil texture directly influences the Dunite behavior, since in clayey soils, changes in pH values respond linearly to the increment of the Dunite rates, whereas in the sandy soil, due to the low soil buffering, the pH values are difficult to change with the increase of Dunite rates (Barbosa et al. 2008). This increase in pH values is an important characteristic of rock dust, mainly because it contains 24% of

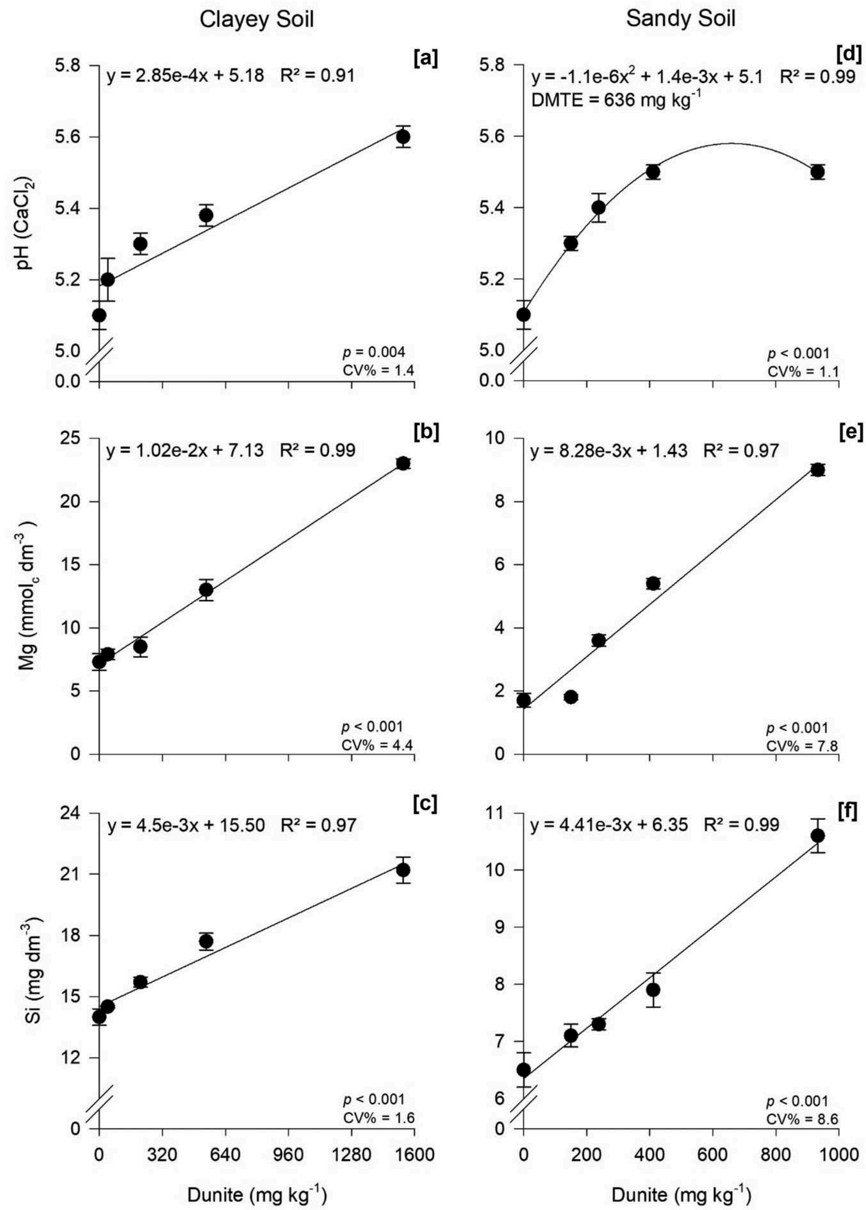

Figure 4. pH (a), Mg (b) and Si (c) contents in clayey soil after soybean cultivation under Dunite rates. pH (d), Mg (e) and Si (f) contents in sandy soil after soybean cultivation under Dunite rates.

MgO and 51% of SiO_2 in its composition, which are materials with high power of neutralization of the active acidity of the soil (Castro and Crusciol 2013; Crusciol et al. 2016). The increase of pH, besides bringing benefits to the chemical attributes, it is also beneficial to the Mg and Si contents, besides increasing the cation-exchange capacity (CEC) and the base saturation, and it also has a high potential to stimulate the microbiological activity of the soil, guaranteeing the selection of microorganisms that are beneficial to the system (Silva et al. 2012; Stevenson and Cole 1999).

As for Mg and Si, clayey soil naturally presents higher amounts of these elements when compared to sandy soil, mainly due to the higher cation retention capacity in their soil colloids (Quaggio 2000).

On the other hand, it should be noted that the Mg contents increased by 3.2 and 1.5 times when comparing the contents obtained in the absence of Dunite application, while the soil Si contents increased by 6.4 and 1.7 times under the same conditions for clayey and sandy soil, respectively. This fact indicates that the soil of clayey texture, for having higher retention capacity of water, SOM and consequently higher microbiological activity (Silva et al. 2012), may have presented a greater decomposition of minerals, and besides that, the organic acids extruded by plants may also have helped in this availability of nutrients (Marschner 2012). If we consider that in the sandy soil the availability of nutrients to the system is slower when compared to the clayey soil, this fact can be considered advantageous, since it can meet the demand of the plants for a long period and reduce possible losses by leaching (Silva et al. 2012).

Conclusions

The Mg and Si content in the plant increase with the use of Dunite, as well as the contents of these elements in the soils. The use of Dunite also promotes the correction of soil acidity (pH). In both soils (clay and sand soil), the increment of rates provides higher contents of reducing sugars and sucrose, and lower contents of leaf starch. There is a greater vegetative growth, filling, and yield of soybean grains with the use of rock dust in a Rhodic Hapludox with different levels of clay.

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