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LIME AND GYPSUM MANAGEMENT REGIMES: SHORT TERM SOIL CHEMICAL PROPERTIES ALTERATIONS AND INITIAL MAIZE GROWTH

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ABSTRACT

The objective of this work was to evaluate the short-term chemical changes in the soil and the initial maize growth as a function of different lime and gypsum management regimes. An experiment was set up in PVC tubes and the effects were evaluated at depths of 0-15cm and 15-30cm after 2 months. A second experiment was carried out in pots where maize was planted, and aerial and root system development were evaluated. The use of limestone and gypsum was tested separately, applied both at the same time and spaced one month apart, plus a control treatment. The application of limestone and gypsum at the same time and only limestone were the treatments that caused the most changes in the soil in the 0-15cm layer after 2 months. The combination of limestone and gypsum also increased root growth and therefore may be an interesting strategy for short-term soil correction.

Keywords: Acidity, aluminum, soil correction, root system, *Zea mays*

REGIMES DE MANEJO DE CALCÁRIO E GESSO: ALTERAÇÕES DE CURTO PRAZO NAS PROPRIEDADES QUÍMICAS DO SOLO E CRESCIMENTO INICIAL DO MILHO

RESUMO

O objetivo desse trabalho foi avaliar as alterações químicas de curto prazo ocorridas no solo e o crescimento inicial do milho em função de diferentes manejos de calcário e gesso. Foi instalado um experimento em tubos de PVC e os efeitos foram avaliados nas profundidades de 0-15cm e 15-30cm após 2 meses. Um segundo experimento foi realizado em vaso onde foi plantado milho, e foram avaliados o desenvolvimento aéreo e do sistema radicular. Foram testados o uso de calcário e gesso isoladamente, aplicados ambos ao mesmo tempo e espaçados em um mês, mais um tratamento controle. A aplicação de calcário e gesso ao mesmo tempo e somente calcário foram os tratamentos que mais provocaram alterações no solo na camada de 0-15cm após 2 meses. A combinação de calcário e gesso também provocou aumento das raízes e, portanto, pode ser uma estratégia interessante para correção do solo de curto prazo.

Palavras-chave: Acidez, alumínio, correção de solo, sistema radicular, *Zea mays*

INTRODUCTION

Much of the agricultural land in Brazil is found under tropical climate, with high temperatures and rainfall, which promotes intense weathering processes, leading to soils with low nutrient content and intense acidity (ALVARES et al., 2013; FAGERIA & NASCENTE, 2014; POPPIEL et al., 2019). This condition causes an impediment to proper root development and consequently reduction of crop productivity (ALCÂNTARA et al., 2015; RAO et al., 2016; YU et al., 2011). Particularly, maize productivity is strongly affected, although it can be improved with practices that reduce surface and sub-surface soil acidity (CAIRES et al., 2008; NORA et al., 2017; UZOMA et al., 2011).

Active acidity and exchangeable acidity are detrimental to crop growth. pH is the measure of active acidity (H^+ in soil solution), while exchangeable acidity refers to the Al^{3+} occupied on the cation exchange capacity (CEC) (LEPSCH, 2011). Limestone (calcium/magnesium carbonate) is used on a large scale to correct soil acidity, reducing the active acidity of the soil, consequently increasing the pH, by converting some hydrogen ions into water. With a pH_{water} above 5.5, Al precipitates and its toxic action is eliminated (LOPES et al., 1990). The base saturation methodology is the most used recommendation for liming in the state of São Paulo and is aimed at correcting acidity on the superficial soil layers (RAIJ et al., 1997).

Agricultural gypsum is usually employed to manage sub-surface Al^{3+} due to its high mobility. It is composed of hydrated calcium sulfate ($CaSO_4.2H_2O$) and after being applied to the soil, it dissociates into Ca^{2+} and SO_4^{2-} ions that infiltrate into deeper layers of the soil profile. Sub-surface Ca^{2+} replaces Al^{3+} ions from the exchange sites in the soil, which in turn reacts with SO_4^{2-}, forming aluminum-sulfate complexes, which are not toxic to plant roots (PRIMAVESI & PRIMAVESI, 2004; VITTI et al., 2015). With the removal of Al^{3+} in depth, there is a better distribution of roots deep in the soil, allowing plants higher water and nutrient absorption (SOUSA et al., 2005). There are several methodologies to recommend gypsum (SOUSA et al., 2005), but the most used in the state of São Paulo is based on the soil clay content (RAIJ et al., 1997).

Most studies evaluating the effects of lime and gypsum on soil acidity demonstrate the long and medium term results. Anderson et al. (2020) found that the combined application of lime and gypsum is more effective than applying lime alone ten years, two years and eight months and 1 year after application. Fontoura et al. (2019) did not find a synergistic effect of combined application on soil properties or maize productivity after 11 years. On the other hand, the same authors found that the application of gypsum alone was more effective to increase Ca levels after 11 months, whereas the application of lime alone was more effective in correcting soil acidity. Other studies also show the results in a timeframe varying from 1 to 10 years (CAIRES et al., 2011; CRUSCIOL et al., 2019; INAGAKI et al., 2016).

Those results have their practical application in farms with moderate to high level of technification, where a proper monitoring system allows to evidence the long-term benefits of the adopted soil management (PIVOTO et al., 2018; RHEINHEIMER et al., 2018). However, most Brazilian farms do not fall into this system, due to the low level of technology applied. In such farms, the soil acidity correction is decided by the farmer without taking into consideration results of soil analysis. In some cases, planting is carried out without even correcting soil acidity (OLIVEIRA & QUARTUCCI, 2021; SANGALLI et al., 2014; SANTANA et al., 2015).

Therefore, there is a knowledge gap of soil acidity management in cases where no previous management has been applied, such as long-term fallow areas or even areas that have been long cultivated, but no soil acidity correction management was applied in the past. In such cases, short term results are needed in order to subsidize management choices in regard to lime and gypsum amendments. Based on that, the aims of this study are to evaluate the short-term soil chemical alterations after different lime and gypsum management regimes and to determine the influence of such management regimes on the initial development of maize.

MATERIAL AND METHODS

We conducted two experiments in the city of Tatuí, State of São Paulo, Brazil. The Köppen climate classification is humid subtropical, oceanic climate without dry season and with hot summer Cfa, with an average annual temperature of 19.8°C and cumulative annual rainfall of 1215 mm (ALVARES et al., 2013).

The first experiment aimed at understanding the short-term chemical modifications in the soil parameters. In February 2019 we filled 10 cm diameter and 40 cm height PVC tubes with 30 cm of soil and placed them standing inside a greenhouse. The soil was collected from a ravine in a park in Tatuí at around 20cm deep. The chemical soil attributes prior to the installation of the experiment were: organic matter 17 g dm^{-3}, pH-$CaCl_2$ 4.6, exchangeable Al 2.0 $mmol_c$ dm^{-3}, Ca 6 $mmol_c$ dm^{-3}, Mg 3 $mmol_c$ dm^{-3}, K 1.1 $mmol_c$ dm^{-3}, P 6 mg dm^{-3}, S-SO_4 10 mg dm^{-3}, CEC 48.1 $mmol_c$ dm^{-3}, base saturation 21.0% and aluminum saturation 16.5%. The physical composition of the soil was 63.2% clay, 35.6% sand and 1.2% silt.

We covered the tube bottom edge with a plastic net and a lid with small holes, in order to allow the water to flow but prevent the soil from leaking. We also made 2 internal circles with PVC glue, in order to diminish the preferential water drainage through the PVC tube wall (WERLE et al., 2008). We followed a complete randomized design, with six treatments and three repetitions. The treatments consisted of different management time regimes for lime and gypsum: T1) without lime and gypsum application (control); T2) only lime application; T3) only gypsum application; T4) gypsum application 30 days after the lime application (L and G+30); T5) lime application 30 days after the gypsum application (G and L+30) and; T6) lime and gypsum applied at the same time. Lime (51% CaO, 0% MgO and 86 effective calcium carbonate equivalents ECCE) and gypsum (17% Ca and 13% S) were applied homogeneously on the soil surface in the tube without incorporation. For lime, we followed the methodology of (RAIJ et al., 1997) aiming at a base saturation of 80%, resulting in a dose of 3.3 t ha^{-1}. For gypsum the recommendation was based on the clay content (RAIJ et al., 1997), totaling 3.8 t ha^{-1}. We simulated a weekly rainfall of 20mm by applying water on the soil surface, dividing this amount into two equal applications every Tuesday and Friday. The water was slowly poured on the soil surface inside the tubes, in order to avoid soil disturbances and to allow the water to homogeneously infiltrate in the tube. Two months after the beginning of the experiment, we cut the tubes at 15 cm height from the base, resulting in two samples of 0-15cm and 15-30cm deep. We then determined the chemical properties following methodology of Raij et al. (2001).

The second experiment aimed at evaluating the initial maize development under different lime and gypsum management regimes. We filled pots of 25 liters and 30cm height with the same soil used in the first experiment. Also, the same treatments, lime and gypsum doses and irrigation regime were applied, simultaneously with the first experiment. The pots were located inside a

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greenhouse in a randomized blocks design, with 4 repetitions. Two months after we filled the pots (when the first experiment ended), we sowed 3 maize seeds per pot and 15 days after emergence we performed a thinning, leaving only the most vigorous plant. We applied mineral fertilizer 04-28-08 in the dose of 715 kg ha^{-1} at planting and 178 kg ha^{-1} of urea and 67 kg ha^{-1} of KCl, 25 days after plant emergence, based on Raij et al. (1997). After emergence, the irrigation followed the same regime and weeding was performed weekly by hand.

Sixty-six days after emergence, when the plants were at phenological stage V8, we cut the plants close to the ground and the shoot green mass (SGM) mass determined. The shoot height (SH) was determined by laying the plant on a table and measuring the distance from the base to the last extended leaf with a measuring tape. The soil was then washed on a sieve and the roots were carefully separated. We then cut the root 15cm below the base, resulting in a 0-15cm and a 15-30cm portion. The roots were dried at 65 ˚C until constant weight and the dry mass determined, resulting in root dry mass from 0 to 15 cm (RDM015), root dry mass from 15 to 30 cm (RDM1530) and root total dry mass (RTDM).

For the first experiment we employed Shapiro-Wilk test to check for normality and all variables presented non normal distribution. We then performed non-parametric Kruskal-Wallis test to determine differences among treatments within the same depth (0-15 cm and 15-30 cm) and Mann-Whitney test to determine differences between the depths in a treatment. For the second experiment, we also employed Shapiro-Wilk test to check for normality. Shoot green mass presented non normal distribution and was transformed to normal using logarithm transformation. We then performed ANOVA and *post hoc* Duncan test to check for differences among treatments. All analysis were performed in SPSS version 27 at 5% significant level ($p<0.05$).

RESULTS AND DISCUSSION

Soil chemical attributes

The management regimes adopted resulted in different soil chemical properties after two months, mostly in the 0-15cm layer. The application of lime and gypsum simultaneously (T6) had the highest influence on pH, although not significantly different from applying only lime (T2). The application of lime and gypsum at different times (T4 and T5) did not differ between them, but applying gypsum first and lime later (T5) was less effective than applying both at the same time. For the 15-30cm layer, there was no significant difference between control and any treatment, although applying only lime or lime and gypsum together resulted in higher pH than when applying only gypsum. All treatments differed between the two depths evaluated, except for control, indicating that any management had a pronounced influence below 15cm on soil pH (Figure 1).

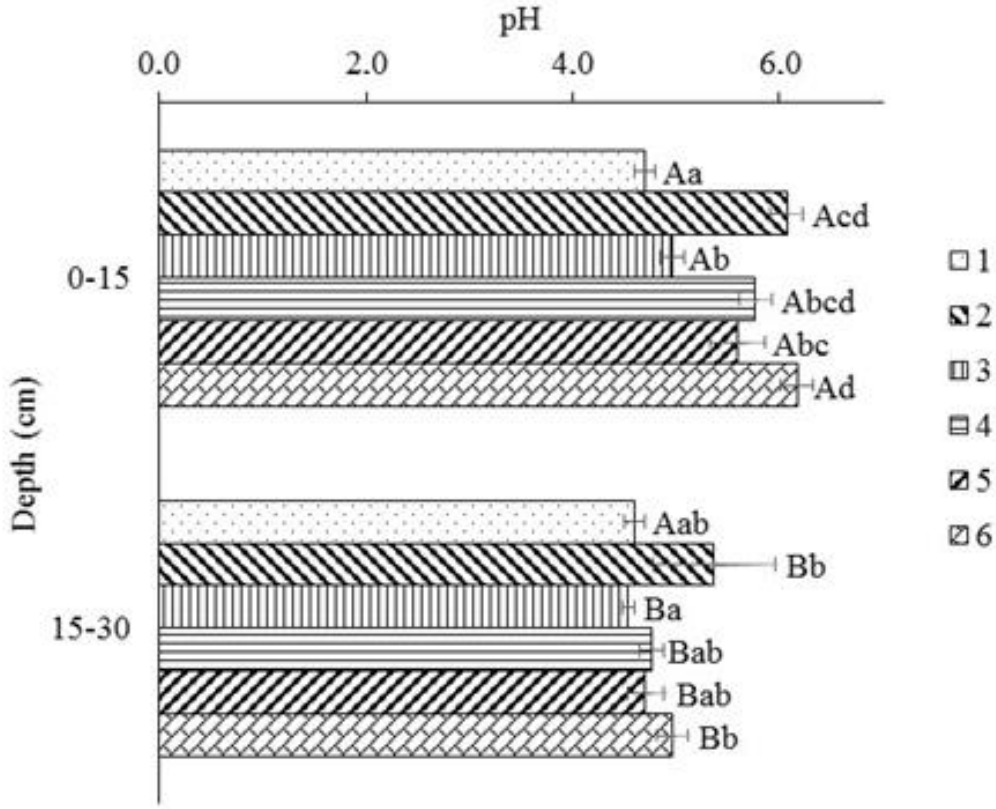

Figure 1. Soil pH after different lime and gypsum management regimes, at depths of 0-15 and 15-30 cm. Error bars represent +-1 standard deviation. Averages followed by the same uppercase letter (comparison between the depths of a treatment) and by the same lowercase letter (comparison among different treatments within the same depth) do not differ statistically ($p \leq 0.05$), Tatuí, São Paulo State, May 2019.

For Al_{sat} in the 0-15cm layer, all treatments resulted in lower values compared to control. Yet, all management regimes that applied lime achieved lower exchangeable acidity than only gypsum. We found no significant differences among the treatments in the 15-30cm layer. However, for treatment 2, the comparison of depths did not show statistical difference, indicating that it might have had an effect below 15cm (Figure 2).

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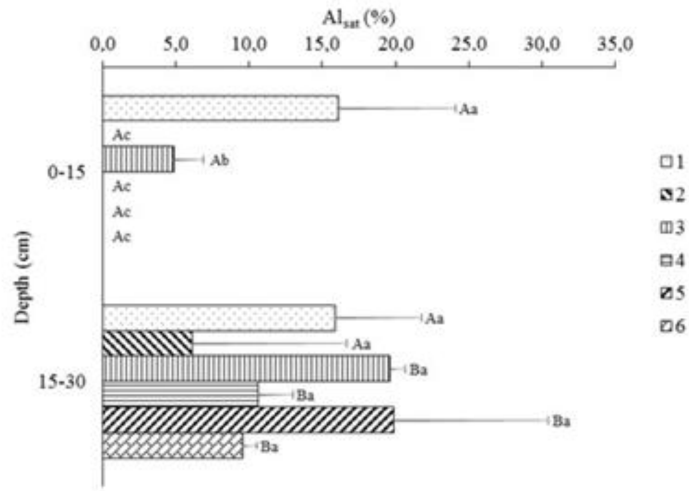

Figure 2. Aluminum saturation (Al_{sat} %) in the soil after different lime and gypsum management regimes, at depths of 0-15 and 15-30 cm. Error bars represent +1 standard deviation. Averages followed by the same uppercase letter (comparison between the depths of a treatment) and by the same lowercase letter (comparison among different treatments within the same depth) do not differ statistically ($p \leq 0.05$), Tatuí, São Paulo State, May 2019.

In regard to nutrients, all management regimes increased the Ca content in the top layer, but not in the lower layer. For S, all treatments that applied gypsum resulted in higher content of this nutrient in the 0-15cm layer. Similarly to Ca, no management regime resulted in higher S content in the 15-30cm layer (Figures 3 and 4).

Our results showed alterations in the soil pH after two months of amendments. Even though most studies evaluate the long-term effect of lime and gypsum, soil chemical alterations seem to occur in the first months after application. Fontoura et al. (2019) evaluated the effects of lime 1 and 11 years after lime application, concluding that amendments had an effect after 1 year and lasted until 11 years after application. Caires et al. (2003) evaluated pH at 11, 23 and 35 months after liming and found statistically higher pH in the 0-5cm layer after 11 months of lime application. Yet Amaral et al. (2004) evidenced statistically higher pH only four weeks after lime application in a 22 cm soil column in a PVC tube, irrigated with a weekly 35mm rainfall simulation. They also analyzed the leached water from the tubes, and found that the first rainfall was responsible for the highest alterations, denoting immediate liming effect. Finally, Alcarde et al. (1989) in an experiment with soil incubation with different lime types for 90 days, found that there was an increase in soil pH up to 17 days, which remained constant after this period.

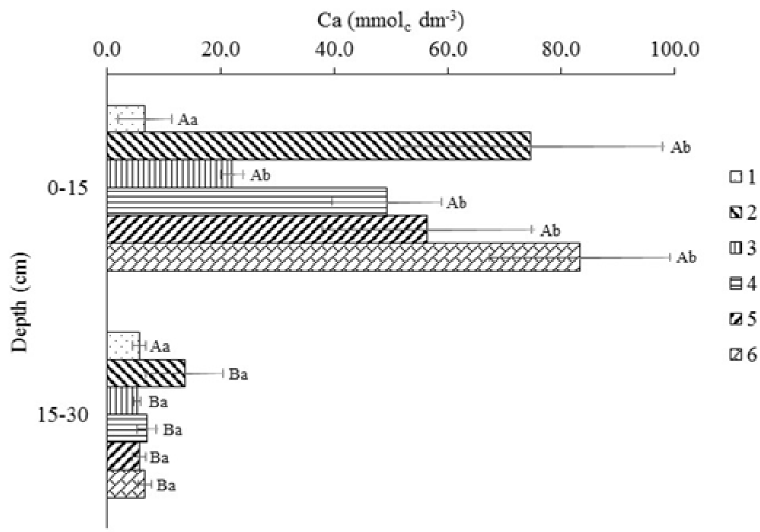

Figure 3. Soil calcium content (Ca, mmol$_c$ dm^{-3}) after different lime and gypsum management regimes, at depths of 0-15 and 15-30 cm. Error bars represent +-1 standard deviation. Averages followed by the same uppercase letter (comparison between the depths of a treatment) and by the same lowercase letter (comparison among different treatments within the same depth) do not differ statistically ($p \leq 0.05$), Tatuí, São Paulo State, May 2019.

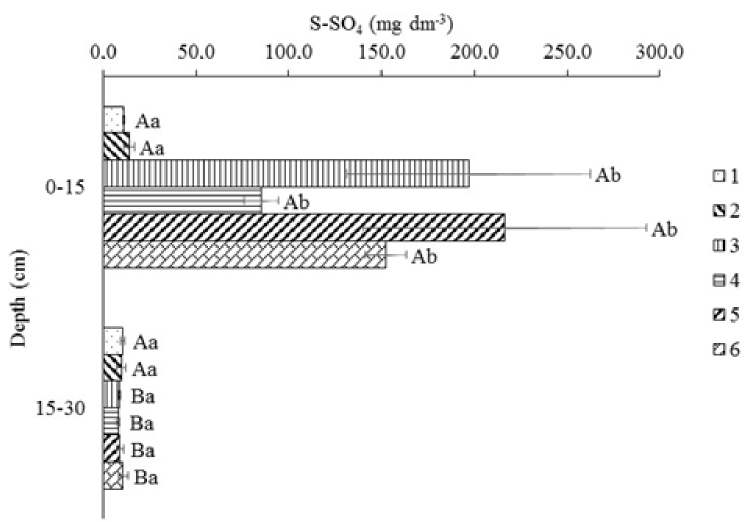

Figure 4. Soil sulfur content (S-SO_4, mg dm^{-3}) after different lime and gypsum management regimes, at depths of 0-15 and 15-30 cm. Error bars represent +-1 standard deviation. Averages followed by the same uppercase letter (comparison between the depths of a treatment) and by the same lowercase letter (comparison among different treatments within the same depth) do not differ statistically ($p \leq 0.05$), Tatuí, São Paulo State, May 2019.

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The results of lime and gypsum application are also expressed in sub-surface, even though it might take longer to have an effect in deeper layers, since lime must be in contact with the soil to react (PRIMAVESI & PRIMAVESI, 2004). In our study, the treatments where only lime was applied and where lime and gypsum were applied together resulted in higher pH in the 15-30cm layer, compared to the only gypsum treatment. Caires et al. (2003) found an increase in the soil pH in the 40-60cm layer after 11 months when lime was incorporated. Also, Fontoura et al. (2019) showed an increase in pH in the whole soil profile down to 60cm after 1 year. Amaral et al. (2004) concluded that the fast soil alterations in the 20cm column was due to the transport of lime particles that did not react in the soil surface and also due to the products of lime dissolution through the soil profile.

The application of only gypsum increased soil pH in the 0-15cm layer, compared to the control treatment, even though it was significantly lower than only lime or lime and gypsum together treatments. Indeed, gypsum promotes several soil chemical reactions, which can result in pH increase (MENZIES et al., 1994). Actually, it can have a positive, negative or neutral effect on pH (SMITH et al., 1994), and soils with high capacity of SO_4 sorption can present an increase (BLUM et al., 2013). An increase in the pH in sub-surface after gypsum has been reported in other long term studies (CAIRES et al., 2003, 2004). In our study, no treatment that applied gypsum resulted in significantly higher pH in the 15-30cm layer, probably due to the limited duration of the experiment.

All treatments promoted a decrease in the Al_{sat} in the 0-15cm layer. Yet, all treatments that applied lime, alone or in combination with gypsum, were more effective than only gypsum. Interestingly, there was no statistical difference between both layers when applied only lime, denoting its action in the sub-surface layer. Nonetheless, the same trend in pH was not observed. Anderson et al. (2020) observed similar results of our study, i.e., a more pronounced effect of lime on Al than pH. According to the authors, small changes in pH result in greater change in Al, implying that Al is more sensitive to lime application than pH. In regard to depth, Caires et al. (2011) also found a reduction in Al down to 60cm depth, showing than lime can had an effect in sub-surface layers.

For Ca in the 0-15cm layer, there was no difference between the treatments, but all increased its levels compared to control. For the 15-30cm layer, any significant effect could be observed.

Fontoura et al. (2019) also found higher Ca content after liming, but limited to the 0-10cm layer after 1 year. Yet, they found higher Ca when gypsum was applied, contrasting with our results, where only liming achieved average of 75 $mmol_c\ dm^{-3}$ and the application of only gypsum resulted in 22 $mmol_c\ dm^{-3}$, although without statistical difference. On the other hand, Anderson et al. (2020) found that the combination of lime and gypsum was more effective than applying them alone. In our work, the combination of lime and gypsum resulted in the higher Ca contents, even though without statistical difference. In the medium and long term, it is expected an increase of Ca in the 15-30cm layer, especially in the treatments where gypsum was used, due to a higher Ca solubility and mobility in the soil profile (CAIRES et al., 2003; CAIRES et al., 2011).

We did not observe an increase in the S content in the 15-30cm. S derived from gypsum was found in sub-surface layers after 8 years (CAIRES et al., 2011), forty-three months (CAIRES et al., 2004), thirty-two months (ANDERSON et al., 2020), and even twenty months (CAIRES et al., 2003) after gypsum application. The downward sulfate movement varies with soil type, and is slower in high clay content soils (CAIRES et al., 2004). In our study, the soil with 63.2% clay content might present a high sulfate sorption capacity, which explains the lack of S in the 15-30cm layer after 2 months.

Root dry mass

Applying gypsum first and lime 30 days later caused an increase in root development. The total root mass of treatment 5 (G and L+30) was 26.8 g $plant^{-1}$, an increase of 13.0 g $plant^{-1}$ compared to the control. There was a homogenous increase in each layer, being 6.3 g $plant^{-1}$ in the 0-15cm layer and 6.8 g $plant^{-1}$ in the 15-30cm layer (Table 1). However, this represents a 119% increase in the top layer, and a 79% increase in the bottom layer. The other treatments did not differ from the control, but did not differ from treatment 5 either, indicating that this could be a trend towards a responsive treatment to the end of the maize cycle.

Caires et al. (2004) found higher root concentration in the 0-10cm layer when lime was applied, but did not find any improvement when lime was used together with gypsum. In our work, the initial root development of maize was positively influenced by the combination of both, although they were applied in a time difference of 30 days between them. Treatment 5 presented the highest content of S in the 0-15cm layer. Yet, Caires et al. (2004) found that maize productivity was higher when Ca saturation was 56%. In our work, the treatment that had the closest figure to this was treatment 5, with a Ca saturation of 63% (data not shown). Therefore, a higher S content

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and an appropriate Ca saturation might explain the higher root growth, but the soil alteration promoted by lime and gypsum application are manifold and difficult to be isolated (CAIRES et al., 2004).

Table 1. Maize root dry mass in different layers, sixty-six days after emergence according to the lime and gypsum management regime. RDM015: root dry mass from 0 to 15 cm; RDM1530: root dry mass from 15 to 30 cm; RTDM: root total dry mass. Averages followed by the same letter in the row do not differ statistically ($p \leq 0.05$), Tatuí, São Paulo State, May 2019.

Treatment	RDM015 (g plant^{-1})	RDM1530 (g plant^{-1})	RTDM (g plant^{-1})
Control	5.3 a	8.5 a	13.8 a
Only lime	8.3 ab	11.5 ab	19.8 ab
Only gypsum	9.0 ab	10.5 ab	19.5 ab
Lime and gypsum +30	11.0 ab	13.0 ab	24.0 ab
Gypsum and lime +30	11.5 b	15.3 b	26.8 b
Lime and gypsum together	8.5 ab	9.3 ab	17.8 ab
CV%	40.2	35.0	33.3

Shoot height (SH) and shoot green mass (SGM)

In regard to the aboveground development, no treatment resulted in higher growth (Table 2). The average height was 134.4 cm, without statistical difference among treatments and control. As for the height, the shoot green mass was not different when different lime and gypsum management regimes were applied, reaching an average mass of 361.3g at sixty-six days after emergence.

Table 2. Mean shoot height (SH, cm) and shoot green mass (SGM, g plant $^{-1}$) of maize plants sixty-six days after emergence according to the lime and gypsum management regime adopted. Averages followed by the same letter in the row do not differ statistically ($p \leq 0.05$), Tatuí, São Paulo State, May 2019.

Treatment	SH (cm)	SGM (g plant^{-1})
Control	114.5 a	291.8 a
Only lime	131.8 a	356.8 a
Only gypsum	142.3 a	392.8 a
Lime and gypsum +30	142.3 a	397.0 a
Gypsum and lime +30	140.0 a	391.3 a
Lime and gypsum together	135.8 a	338.0 a
CV%	17.8	19.5

Management that promotes higher root growth, without compromising shoot growth, is a strategy of both climate change adaptation and mitigation. It is expected to have more frequent and intense droughts with the aggravation of climate change (PEREIRA et al., 2018). Soil managements that create plants with a better soil profile exploration by the roots increase their ability to withstand water stress, reducing the risks of productivity losses in periods of water shortage (SOUSA et al., 2005). Pauletti et al. (2014) observed an improvement of the chemical soil attributes in the soil profile when gypsum was combined with lime, resulting in higher maize productivity during a water shortage period. Therefore, increasing root development could be an interesting strategy to cope with the adverse effects of climate change like longer drought periods. On the other hand, crops with higher root growth have the potential to mitigate climate change via carbon sequestration. The importance of soil carbon sequestration in croplands has been stressed as one with higher impacts. The 4 per mile initiative, for example, advocates for an increase of 0.4% per year in soil organic carbon in croplands, which could offset emissions for 20 years (MARTIN et al., 2021; MINASNY et al., 2017; SOUSSANA et al., 2019). Since most of the soil carbon comes from the roots (KÄTTERER et al., 2011; RASSE et al., 2005; SOKOL et al., 2019) , management that promotes higher root growth could be implemented as a climate mitigation strategy. In our work, considering a stand of 60,000 plants per hectare, treatment 5 added 780 kg ha^{-1} of dry root to the 0-30cm layer compared to the control. The potential is much higher, considering the full maize cycle and a deeper soil profile.

CONCLUSIONS

We found substantial soil chemical alterations after two months of lime and gypsum application. The most pronounced effects took place on the 0-15cm layer. There was an increase in pH, base saturation and Ca and S levels, in addition to a decrease in the Al saturation. For pH, BS, Al_{sat} and Ca, applying only lime or lime and gypsum at the same time promoted the best results. For S, applying gypsum first and lime 30 days after resulted in higher nutrient content. The treatment with only lime had also a positive effect on Al_{sat} in the 15-30cm soil layer.

No effect was observed on the initial aboveground growth of maize. However, there was a higher root growth when gypsum and lime were applied thirty days apart from each other. The combination of lime and gypsum seem to be a good strategy to promote short term soil chemical improvements and stimulate root growth, which might contribute to an increase in soil carbon sequestration.

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