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RESEARCH ARTICLE
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Lime rates in degraded pasture conversion into agricultural fields in the *Cerrado*/Amazon Rainforest transition zone[1]

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ABSTRACT - Degraded pasture sites conversion to grain production systems is a reality in Mato Grosso, but this process is not always carried out in a proper technical manner. The aim of the present study is to assess soil changes and soybeans and second-crop maize components yield over a three–year time frame due to the addition of high lime rates to the soil at the end of the rainy season in order to implement no-till farming in degraded pasture sites. The experiment followed a randomized block design based on increasing lime rates: 0.0; 3.0; 6.0; 9.0; 12.0 t ha^{-1}, with four replications. The treatments were applied to the soil in April 2019, in Marcelândia Municipality, Mato Grosso State, Brazil. The soil chemical features were analyzed at four different times, from November 2019 to July 2022. Soybeans and maize were grown in the study site throughout the assessment time, and yield components were measured. High lime rates significantly changed pH, Ca and Mg content, base saturation, and these cations' rate in CEC at pH 7, seven months after liming. It happened because of the lime addition to the soil while it was still moist. It was done to make sure of the reaction, as these benefits lasted for the three assessed years. Liming benefits reflected on soybeans and maize cumulative yield at the end of the experimental time. Thus, more robust lime applications during the time the soil is still moist improved fertility and increased crop yield.

Keywords: Base saturation. Lime overdose. Soybean. Maize.

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INTRODUCTION

Soils in Brazil's tropical regions are naturally poor and account for high acid–cation levels due to the parent material and the weathering agents' intensity (Lopes; Guilherme, 2016; Sousa *et al*., 2016). Approximately 28 million hectares of planted pastures in Brazil show signs of degradation (Bolfe *et al*., 2024). If they are converted to agricultural use, they would help increasing the cultivated land. Land use without soil amendments or fertilization, among other factors, has been causing land degradation over the years (Lange *et al*., 2019). However, small changes can open room for immediate benefits (Lange *et al*., 2018).

Recent studies have shown that soil acidity significantly influences nutrient dynamics and annual crops' yield in highly weathered tropical environments (Kolling *et al*., 2025; Oliveira *et al*., 2024). The pH, calcium (Ca^{2+}) and magnesium (Mg^{2+}) content, base saturation (BS) and these cations' distribution within the cation exchange capacity (CEC) are among the most important chemical properties for plant nutrition and soil chemical balance. Liming is the primary management practice to correct soil acidity as it neutralizes aluminum and increases the availability of bases that, in their turn, affect nutrient uptake. Root development improvement, biological nitrogen fixation and nutrient use have efficient positive impact on plant growth and yield (Lima; Araujo, 2024). Adequate base saturation is associated with greater physiological efficiency, improved development of reproductive structures and better fertilizer use in soybeans and maize crops (Kolling *et al*., 2025).

The addition of new areas to the production system is essential to ensure proper early liming application at appropriate rates, its uniform distribution and deep incorporation. It must be done to achieve deeper root growth and increase crop tolerance to summer drought periods (Moraes *et al*., 2023; Quaggio; Raij, 2022). These soil management practices lead to better root distribution throughout the soil profile and to higher grains' yield (Bellinaso; Vargas; Rheinheimer, 2021).

On the other hand, liming failure in the *Cerrado* region and in areas surrounding it, is often associated with its superficial incorporation into dry soils. This condition hinders the proper mixing between the amendment and the soil. Furthermore, lack of moisture reduces soil amendment's effectiveness, which results in low efficiency and in lack of effects on the first crop.

Degraded pasture conversion into agricultural land is common in Northern Mato Grosso State. Nevertheless, lime application at proper rates during the first crop season is limited by the high cost and the logistics to transport the material, among other costs. This operation is usually carried out at the end of the dry season (August/September) when soil moisture levels are low. These conditions impair lime incorporation and delay the soil amendment reaction, and it only starts after the October/November rains. This process hinders the development of the newly planted crops. Thus, lime early application and proper incorporation in sites undergoing pasture conversion in Northern Mato Grosso under higher soil moisture conditions can increase soil amendment reactivity and improve crops' initial development.

Accordingly, the present study lied in investigating the effects of adding high lime rates in deep soil layers at the end of the rainy season in sites facing degraded pastureland conversion into agricultural use land.

MATERIAL AND METHODS

The experiment was conducted in Marcelândia municipality, Mato Grosso State, Brazil, at latitude 10°52'48.5" S, longitude 54°36'44.6" W, and mean altitude of 300 m. The soil in the site is classified as Dystrophic Red-Yellow Latosol (Oxisol). The region's climate is tropical with dry winter; it is classified as Aw according to the Köppen-Geiger classification and featured by a rainy season from October to March and a dry season from April to September (Souza *et al*., 2013). Mean yearly temperature is 25 °C, and mean yearly rainfall is 2.100 mm (Embrapa, 2024). Figure 1 summarizes the chronological sequence of primary field activities alongside concurrent rainfall and temperature data.

The study site was a degraded pasture that had been in use for 10 – 12 years without soil amendments. However, it was used for rain-fed rice during the 2018/19 crop season, without fertilization. Soil samples were taken from the 0 – 20 cm layer in early April 2019, after the rice harvest, and the results were pH_{H2O} = 5.15, pH_{CaCl2} = 4.40, P = 1.13 mg dm^{-3}, K = 26.3 mg dm^{-3}, Ca = 0.34 $cmol_c$ dm^{-3}, Mg = 0.25 $cmol_c$ dm^{-3}, Al = 0.20 $cmol_c$ dm^{-3}, H + Al = 6.40 $cmol_c$ dm^{-3}, CEC = 7.1 $cmol_c$ dm^{-3}, OM = 26.5 g kg^{-1}, S = 8.0 mg dm^{-3}, BS = 9.3%, B = 0.19 mg dm^{-3}, Cu = 0.88 mg dm^{-3}, Mn = 6.63 mg dm^{-3}, Zn = 0.45 mg dm^{-3}. Soil texture comprised 489 g kg^{-1} clay, 176 g kg^{-1} silt and 335 g kg^{-1} sand.

Figure 2 depicts the field work, which following the experiment's implementation in April 2019. It is recommended to increase base saturation to 50% in rain-fed systems for soybeans and maize in *Cerrado* soils, and to make sure that Mg content ranges from 0.5 to 1.0 $cmol_c$ dm^{-3}, minimum (Embrapa, 2013; Sousa; Lobato, 2004). Quaggio and Raij (2022) recommend increasing BS to 70% in these crops. Based on soil analysis and soil amendment features, application rate close to 5.7 t ha^{-1} was required for the 0 – 20 cm layer to achieve 70% BS. Regional studies have shown that the dose estimated through the base saturation method does not reach the estimated value (Lange *et al*., 2021, 2022). This finding explains why higher-than-usual rates were chosen.

Figure 1 - Monthly rainfall (mm) and mean temperature (°C) during the experimental time and the soybeans and maize cultivation at Pindorama Farm, Marcelândia municipality, Mato Grosso State, Brazil (from April 2019 to July 2022). Field work: 1- liming in the first half of April 2019, 2- soil sampling seven months after liming, 3- soybean sowing in November 2019, 4- maize sowing in the first half of March 2021, 5- maize harvest and soil sampling in July 2020, 6- soybean sowing in November 2020, 7- soybean harvest and maize sowing in the first half of March 2021, 8- maize harvest and soil sampling in July 2021, 9- soybean sowing in Oct 2021, 10- soybean harvest and maize sowing in the second half of Feb 2022, 11- soil sampling in July 2022

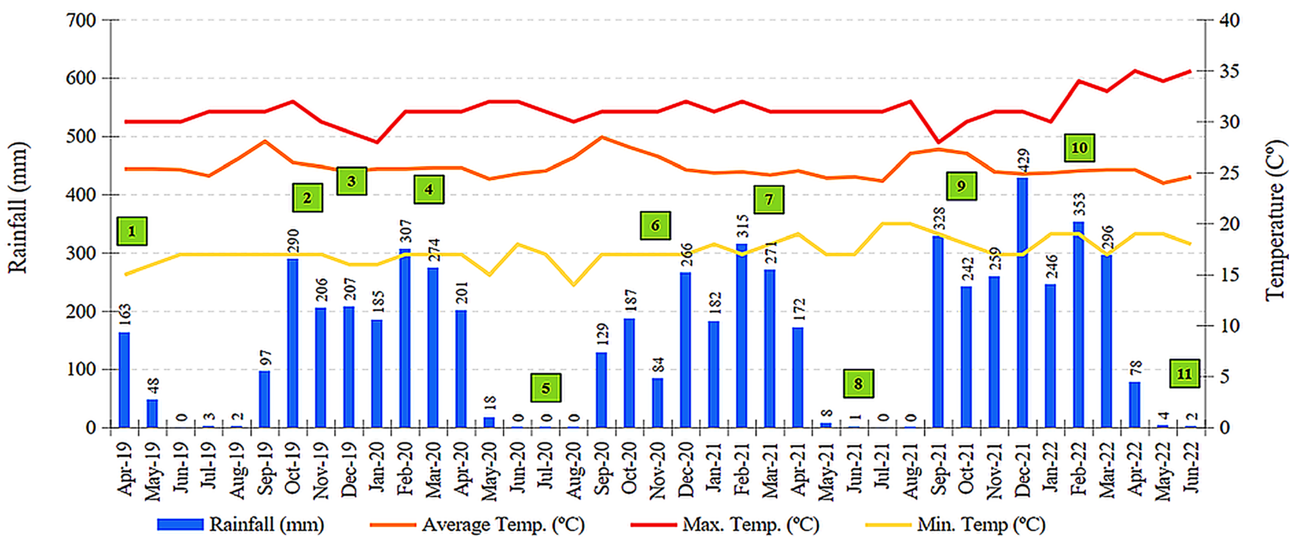
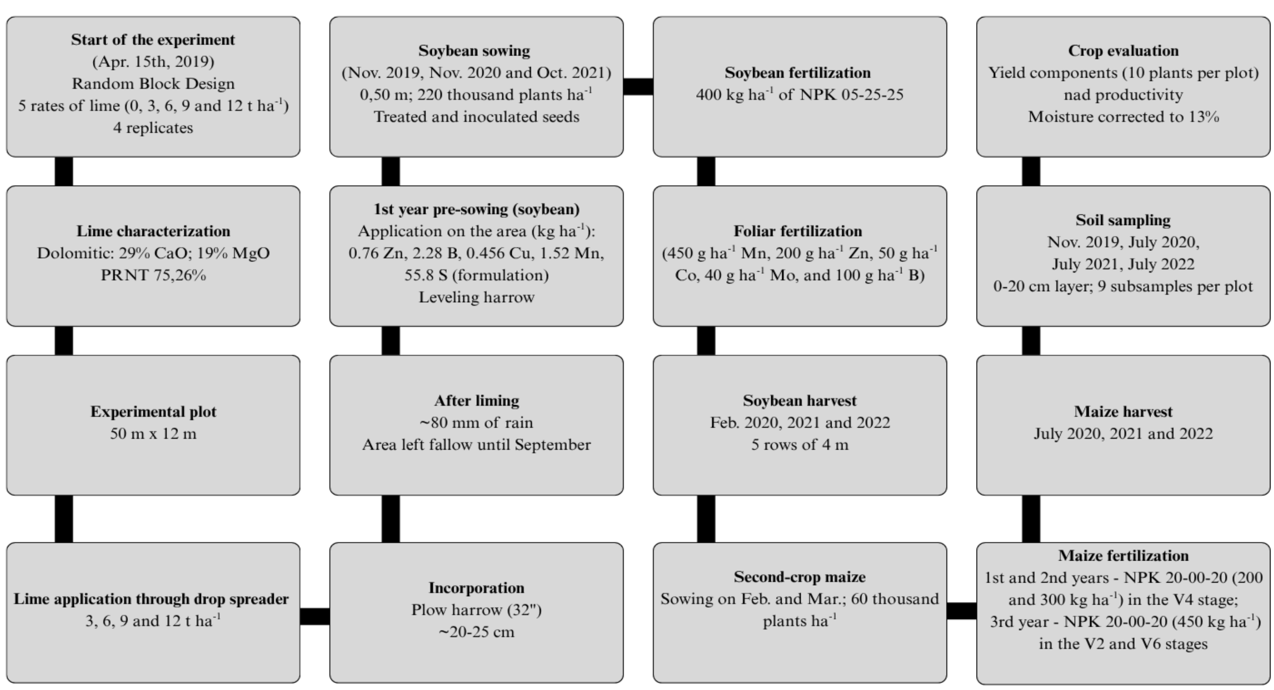


Figure 2 - Flowchart of activities and procedures followed to conduct the study



Liming was performed as follows: 3.0 t ha^{-1} (100% application rate + harrowing), 6 t ha^{-1} (50% rate + harrowing + 50% rate + harrowing), 9 t ha^{-1} (66% rate + harrowing + 33% rate + harrowing), 12 t ha^{-1} (50% rate + harrowing + 50% rate + harrowing). Phytosanitary procedures, cultural practices and NPK fertilization followed the same practices adopted in the rest of the farm. Despite the need for initial phosphorus fertilization, many farmers just make corrections over time due to initial costs associated with land clearing.

Nine individual samples (holes) were collected from each plot with the aid of a Dutch auger for soil sampling (3 points along the last maize row and 6 points between rows) in the 20–cm layer. Soil chemical analyses were conducted based on the method recommended by Embrapa (1997).

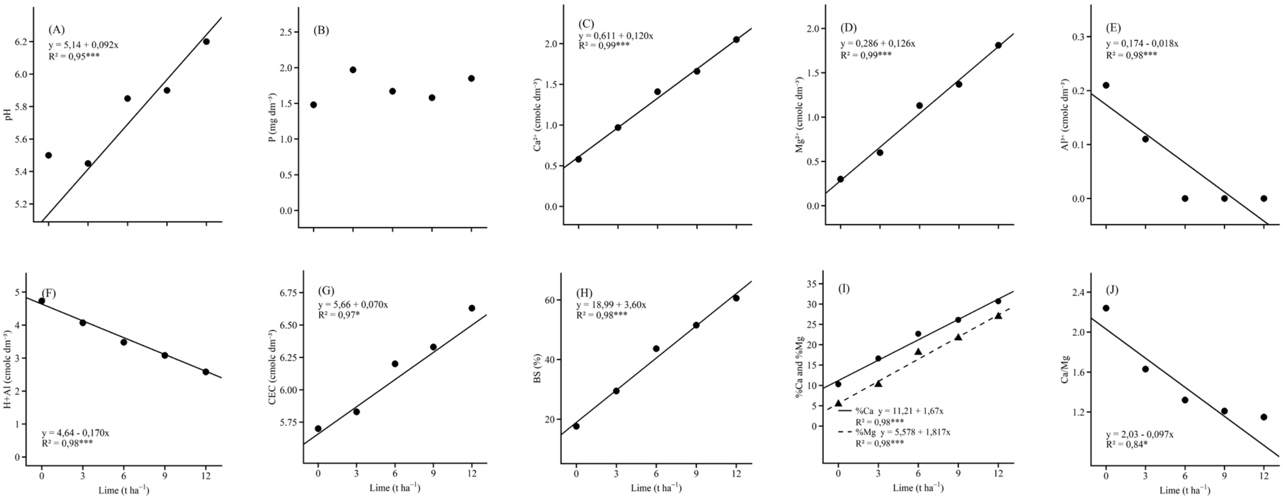
Lime rates data were subjected to analysis of variance through F-test and subsequently analyzed through regression analysis. Data were subjected to Kaiser-Meyer-Olkin test (values greater than 0.50) and Bartlett's test of sphericity (values lower than 0.05) to check the assumptions required for Principal Component Analysis. Variables communality was assessed and those recording values lower than 0.5 were excluded. Only principal components showing eigenvalues higher than 1.0 were selected.

Hierarchical clustering analyses were performed to classify and identify homogeneous data groups. Euclidean distance and Ward's algorithm were used in hierarchical clustering. Results were visualized in dendrogram to identify sample groupings, which were subsequently represented in principal component plots. PERMANOVA was applied to validate the hierarchical groupings; it was followed by pairwise comparisons through permutation tests.

RESULTS AND DISCUSSION

All assessed soil variables had significant effects (Figures 3, 4, 5, and 6), and this finding complies with studies that had used increasing lime rates of lime (Costa *et al*., 2016; Crusciol *et al*., 2016; Esper Neto *et al*., 2019; Moraes *et al*., 2023; Rodrighero; Barth; Caires, 2015). Initial soil pH in April 2019 was 5.1 and it did not change significantly change over time, in the absence of liming. The pH increase was linear to the applied lime rates; it showed appropriate R^2 adjustments and low coefficient of variation. According to this outcome, soil sampling could identify the changes caused by liming in the chemical features. The pH was at its highest rate (6.42) in 2020, 16 months after liming (Figure 4A). It was the only time the 6.0 t ha^{-1} rate reached pH ~6.0. This finding provided the time required to reach the soil amendment reaction peak in acidity neutralization terms. The pH did not reach 7.0 even with the addition of 12 t ha^{-1} lime. It happened because of the buffering effect caused by the soil clay content, by its activity, potential acidity and organic matter content. Studies by Moraes *et al*. (2023) conducted under field conditions and by Santos *et al*. (2024) under controlled conditions have shown that soil pH rarely exceeds 7.0 at lime rates higher than the recommended one. The soil presented potential acidity (H + Al) of 6.4 cmol$_c$ dm^{-3}, 26.5 g kg^{-1} organic matter and 489 g kg^{-1} clay at the start of the study. It certainly impaired pH rise to levels higher than 6.5.

Figure 3 - The pH values in H_2O, phosphorus (P), calcium (Ca^{2+}), and magnesium (Mg^{2+}) content. aluminum (Al^{3+}), potential acidity (H + Al), cation exchange capacity (CEC), base saturation (BS), Ca and Mg rates in CEC, and Ca:Mg ratio in the soil in November 2019 based on the lime rates applied in April 2019 upon the introduction of no-till farming in Marcêlandia municipality, Mato Grasso State, Brazil



The pH was >5.85 and the exchangeable Al was 0.0 $cmol_c$ dm^{-3} seven months after liming (Nov. 2019) at application rates above 6.0 t ha^{-1} (Figures 3A and 3E), which already provided favorable conditions for grain (Quaggio; Raij, 2022; Sousa; Lobato, 2004). Liming, at the right time of year, when the region was receiving rainfall, allowed the soil amendment to react, and it created suitable conditions for soybean cultivation as early as October/November, after seven to eight months. This observation complies with soil Al concentrations, namely: 0.2 $cmol_c$ dm^{-3} at initial sampling and reduced to zero in the 2020 sampling after the application of ≥3.0 t ha^{-1}. A small amount of Al was observed at 3.0 t ha^{-1} in the following years, but there was no exchangeable Al in the soil at rates ranging from 6.0 t ha^{-1} onwards. The lowest H + Al values were observed in the first and second samples: ~4.0 $cmol_c$ dm^{-3}, on average. It rose to 5.30 $cmol_c$ dm^{-3} in the last sampling (Figures 3F, 4F, and 6F, respectively). The variables regulating the soil acidity show that the soil tends to become more acidic after three full crop seasons (three soybean crops and three maize crops). Harvesting and the application of nitrogen fertilizers cause soil acidification, in addition to affect the soil's electrochemical balance and the absorption, extraction and export of nutrients required by crops. Furthermore, prolonged soil use, alone, without nutrient correction or replenishment, causes acidification (Lange *et al*., 2019; Lange; Zandonadi; Gobbi, 2019).

Phosphorus content was only affected in the 2021 samples (Figure 5B), as P levels decreased as the lime application rate increased. From an agronomic perspective, the 2021 values still fall within the very low range (Sousa *et al*., 2016) - below 3.0 mg dm^{-3}. This is a characteristic of newly developed areas in the region, where soil fertility builds up slowly due to high fertilizer costs. The P levels could already be on the average values (reaching 4.6 mg dm^{-3}) in the latest sampling, after three P applications (totaling ~300 kg ha^{-1} of P_2O_5). This process in combination with the appropriate sowing time allowed the crop to benefit from adequate rainfall, which significantly improved maize yield in the last assessed harvest; the average exceeded 9.0 t ha^{-1}.

The Ca and Mg concentrations followed a linear trend in all seasons. The lowest mean Ca concentrations (1.33 $cmol_c$ dm^{-3}) were observed in November 2019 (Figure 3C), seven months after liming. However, the highest lime rate raised the concentration to 2.05 $cmol_c$ dm^{-3}, which improved the nutrient's availability in the soil. Sousa and Lobato (2004) considered Ca levels between 1.5 and 7.0 $cmol_c$ dm^{-3}, and Mg levels between 0.5 and 2.0 $cmol_c$ dm^{-3} to be adequate. The authors consider that Mg should exhibit a minimum value ranging from 0.5 to 1.0 cmolc dm^{-3}. According to Embrapa (2013), Ca values should range from 2.0 to 4.0 $cmol_c$ dm^{-3} (medium) or >4.0 $cmol_c$ dm^{-3} (high); and Mg, from 0.4 to 0.8 or >0.8 $cmol_c$ dm^{-3} in soils with CEC ≥ 8.0 $cmol_c$ dm^{-3} for soybean cultivation.

Mean Ca content in the soil rose to 2.83 $cmol_c$ dm^{-3} in 2022. The levels were ≥3.6 $cmol_c$ dm^{-3} (Figure 6C) at rates >6.0 t ha^{-1}, which is considered adequate. Therefore, the proper incorporation of high lime rates into moist soil allowed greater reaction and residual effect over the years, which is essential for the successful establishment of a No-till Farming System (NTFS). Recent studies have shown higher soybean, maize and bean crops yield under Ca levels ranging from 4.0 to 6.5 $cmol_c$ dm^{-3}, and Mg levels close to 1.5 $cmol_c$ dm^{-3} due to high lime–application rates (Moraes *et al*., 2023).

Figure 4 - The pH values in H_2O, phosphorus (P), calcium (Ca^{2+}) and magnesium (Mg^{2+}) content. aluminum (Al^{3+}) and potential acidity (H + Al), cation exchange capacity (CEC), base saturation (BS), a and Mg rates in the CEC, and Ca:Mg ratio in the soil in July 2020 due to the lime rates applied in April 2019 upon the introduction of no-till farming in Marcêlandia municipality, Mato Grosso State, Brazil

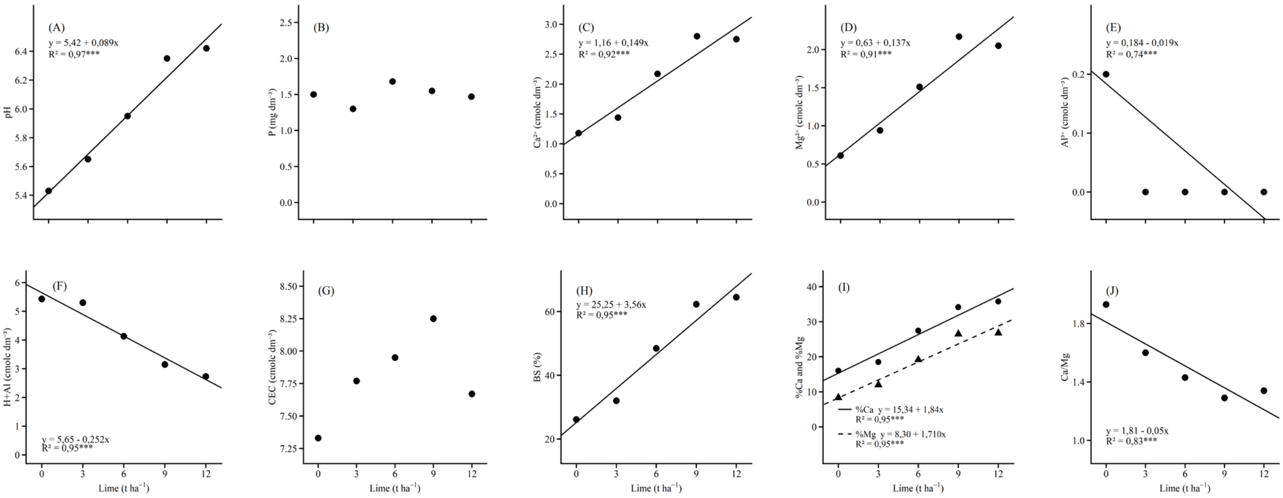
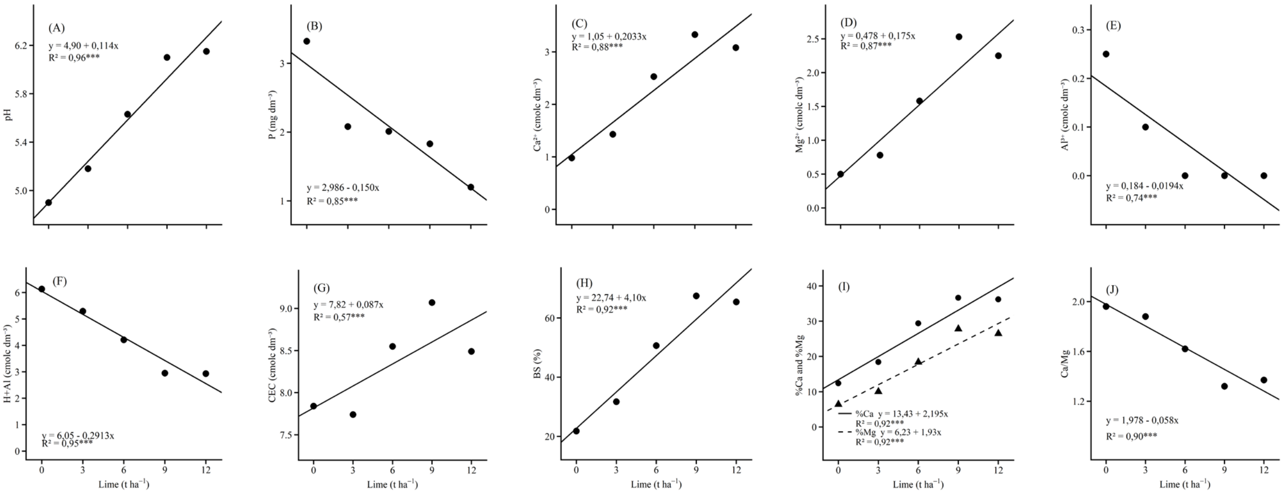


Figure 5 - The pH values in H_2O, phosphorus (P), calcium (Ca^{2+}) and magnesium (Mg^{2+}) content. aluminum (Al^{3+}) and potential acidity (H + Al), cation exchange capacity (CEC), base saturation (BS), Ca and Mg rates in the CEC, and Ca:Mg ratio in the soil in July 2021 due to the lime rates applied in April 2019 upon the introduction of no-till farming in Marcêlandia municipality, Mato Grosso State, Brazil



The initial Mg concentration in the soil was 0.25 $cmol_c$ dm^{-3}, which is considered extremely low by official recommendations (Embrapa, 2013; Quaggio; Raij, 2022; Sousa; Lobato, 2004). Its concentration in the control treatment remained close to 0.5 $cmol_c$ dm^{-3} throughout the study, which limits crop production. However, after lime application, Mg content finally got stabilized (2020); its concentrations got close to 1.5 $cmol_c$ dm^{-3} at 6.0 t ha^{-1} and were approximately 2.2 $cmol_c$ dm^{-3} at the highest rates (Figure 4D). These levels boosted plant growth (Moraes *et al*., 2023).

The application of 0.0, 3.0, 6.0, 9.0 and 12.0 t ha^{-1} lime theoretically added 0.0, 1.55, 3.11, 4.66, and 6.21 $cmol_c$ dm^{-3} Ca; and 0.0, 1.42, 2.84, 4.26 and 5.68 $cmol_c$ dm^{-3} Mg (0 – 20 cm = 2,000,000 dm^{-3}). This finding pointed towards that possibility of soil amendment reaction, even at rates traditionally higher than the recommended ones, which led to a residual effect.

The highest Ca rates in CEC were close to 35% in 2021 and 2022, at the highest application rates (Figures 5J and 6J) - those were relatively low values. The recommended Ca rate for soybeans in soils with CEC ≥8.0 $cmol_c$ dm^{-3} ranges from 35% to 50% (medium) or >50% (high); in soils with CEC <8.0 $cmol_c$ dm^{-3} it ranges from 26% to 34% (medium) or >34% (high) (Embrapa, 2013). The Mg rates were exceeded 20% at application rates >9.0 t ha^{-1}. These values were slightly higher than those recommended in the literature, which caused slight imbalance in the Ca:Mg ratio (< 2:1). This finding could be addressed in the future by using calcitic lime to achieve a better soil balance.

The Ca:Mg ratio always reached less than 2:1 in the current study. It is worth noticing that this ratio's results in the literature are not yet conclusive (Clark *et al*., 1997; Holzschuh, 2007; Lange *et al*., 2021). According to Quaggio and Raij (2022), as long as an adequate Mg content in the soil is ensured, the Ca:Mg ratio is of lesser importance. Furthermore, according to them, experimental results have shown that the Ca:Mg ratio ranging from 2:1 to 30:1 has little effect caused by the nutrient levels when they are not close to the shortage threshold.

CEC at pH 7.0 linearly increased from 2019 to 2021; it rose 1.0 $cmol_c$ dm^{-3} (5.70 in the 0.0 t ha^{-1} treatment to 6.63 in the 12 t ha^{-1} treatment) in 2019 (Figure 3G) and 0.7 $cmol_c$ dm^{-3} in 2021 (Figure 5G). This increase is explained by changes in soil pH, which rose from 5.05 in the 0.0 t ha^{-1} treatment to 6.20 in the 12 t ha^{-1} treatment, in 2019, and from 4.90 in the 0.0 t ha^{-1} treatment to 6.15 in the 12 t ha^{-1} treatment, in 2021. Soil colloids have negative and positive charges, and the negative charges prevail in our soils, although these charges can be permanent or varying, in nature. Variable charges are also called "pH-dependent"; they are affected by rising pH, as organic colloids show increased negative charges due to the dissociation of hydroxyl groups, which increases the CEC (Furtini Neto *et al*., 2001).

The initial base saturation (BS) in the soil in the assessed degraded pasture site was 9.3%.BS was ~60% at the 12 t ha^{-1} treatment seven months after liming (Figure 3H), and it showed significant linear effect across all seasons. This result, as early as seven months, may have emerged from the application to moist soil in April, as rainfall occurred shortly after application (80 mm), before the dry season onset, in combination with 396 mm rainfall in September and October 2019, prior to sampling. Soil tillage promoted the soil amendment reaction (Rheinheimer *et al*., 2018; Santos *et al*., 2024) and also played key role in it, since poor soil amendment mixing into the soil limits its reaction to the surface layer (Costa *et al*., 2016; Rodrighero; Barth; Caires, 2015). The highest BS values were recorded 28 months after liming (Figure 5H). They reached ~65%, which is consistent with other studies that recorded greater responses 2 to 3 years after liming (Crusciol *et al*., 2016; Moraes *et al*., 2023). These values began to decline in 2022, dropped to ~60% at the highest doses (Figure 6H). This findings are coherent with the observations made for pH and H + Al. Only 5.25 t ha^{-1} would be needed to reach this saturation when 65% BS value is obtained to the liming recommendation formula, based on soil base saturation increase ($NC_{(0-20\ cm)} = [(65–9.3) \times 7.1] / 75.26$). BS would reach 136% "theoretical value" at 12 t ha^{-1}. This result, like others that were previously shown, highlighted that the traditional recommendation does not always achieve the desired BS outcomes (Lange *et al*., 2021, 2022; Moraes *et al*., 2023; Rodrighero; Barth; Caires, 2015).

According to soybean yield components, the increased lime rates had significant effect on plant density and on the number of branches per plant (Figure 7). Thousand-seed weight, number of seeds per plant and yield were not affected in the yearly assessment.

Soybean plant density (Figure 7A) was influenced by numerous biotic and abiotic factors. Variations in soil chemical features, such as soil acidity, directly affected seed germination and crop establishment under the herein adopted conditions. In addition, Ca and Mg shortage affects biological nitrogen fixation (BNF), since Ca is essential for nodulation (Malavolta; Vitti; Oliveira, 1997) and root nodules infection caused by nitrogen-fixing bacteria affect plant nutrition and yield (Alves *et al*., 2021), as well as interfere with final plant density. Calcium (Ca) shortage in soybeans also affects growth points, causes root atrophy and kills the apical bud, which delays the emergence of the first leaves, in addition to causing petiole collapse. On the other hand, Mg is essential for chlorophyll formation as it acts as enzyme activator and cofactor for many phosphorylating enzymes. This nutrient's shortage leads to reduced root penetration and expansion (Malavolta; Vitti; Oliveira, 1997). Thus, Ca and Mg supply through liming is essential, besides improving soil pH.

Soybean branching increased due to the higher application rates used in 2019 (Figure 7B). This is one of the factors regulating soybean yield, as it influences the number of reproductive nodes and potential pods, besides being controlled by several factors, such as cultivar, spacing, plant nutrition, water availability, solar radiation and temperature (Mundstock; Thomas, 2005), in addition to the availability of Ca as cementing agent.

No differences in soybean yield were observed after liming during the assessed crop seasons (Figure 7E). However, cumulative yield at the end of the three crop seasons responded to the lime application rates (Figure 8). This is an important parameter to analyze the economic viability of degraded pastures conversion, since the investment is recouped over the years. Yield gain exceeded 2.000 kg ha^{-1} at the highest rates,

Figure 6 - The pH values in H_2O, phosphorus (P), calcium (Ca^{2+}) and magnesium (Mg^{2+}) contents. aluminum (Al^{3+}) and potential acidity (H + Al), cation exchange capacity (CEC), base saturation (BS), Ca and Mg rates in the CEC, and Ca:Mg ratio in the soil in July 2022 due to the lime rates applied in April 2019 upon the introduction of no-till farming in Marcêlandia municipality, Mato Grosso, Brazil

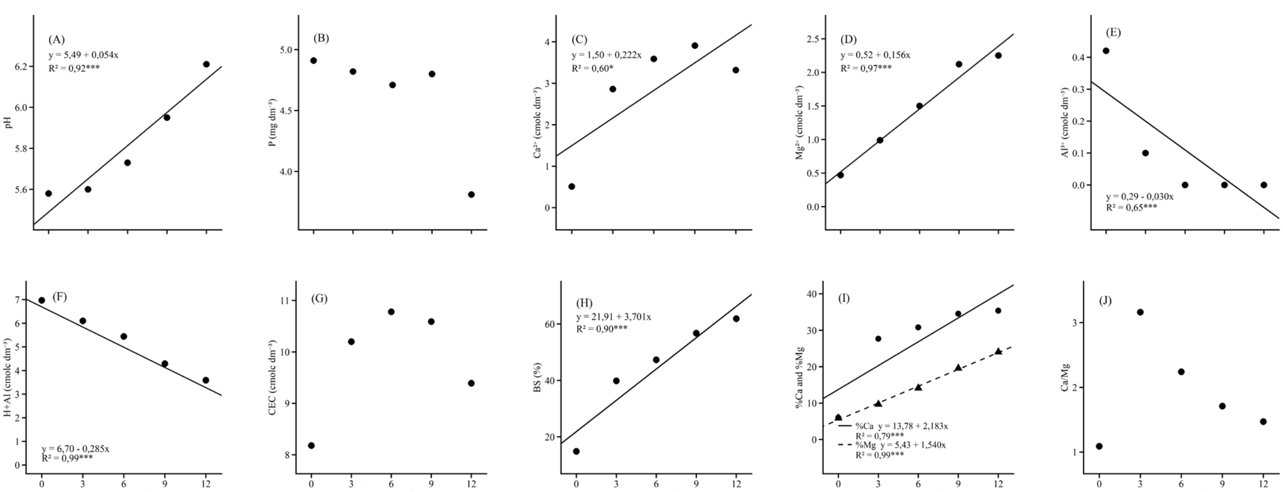
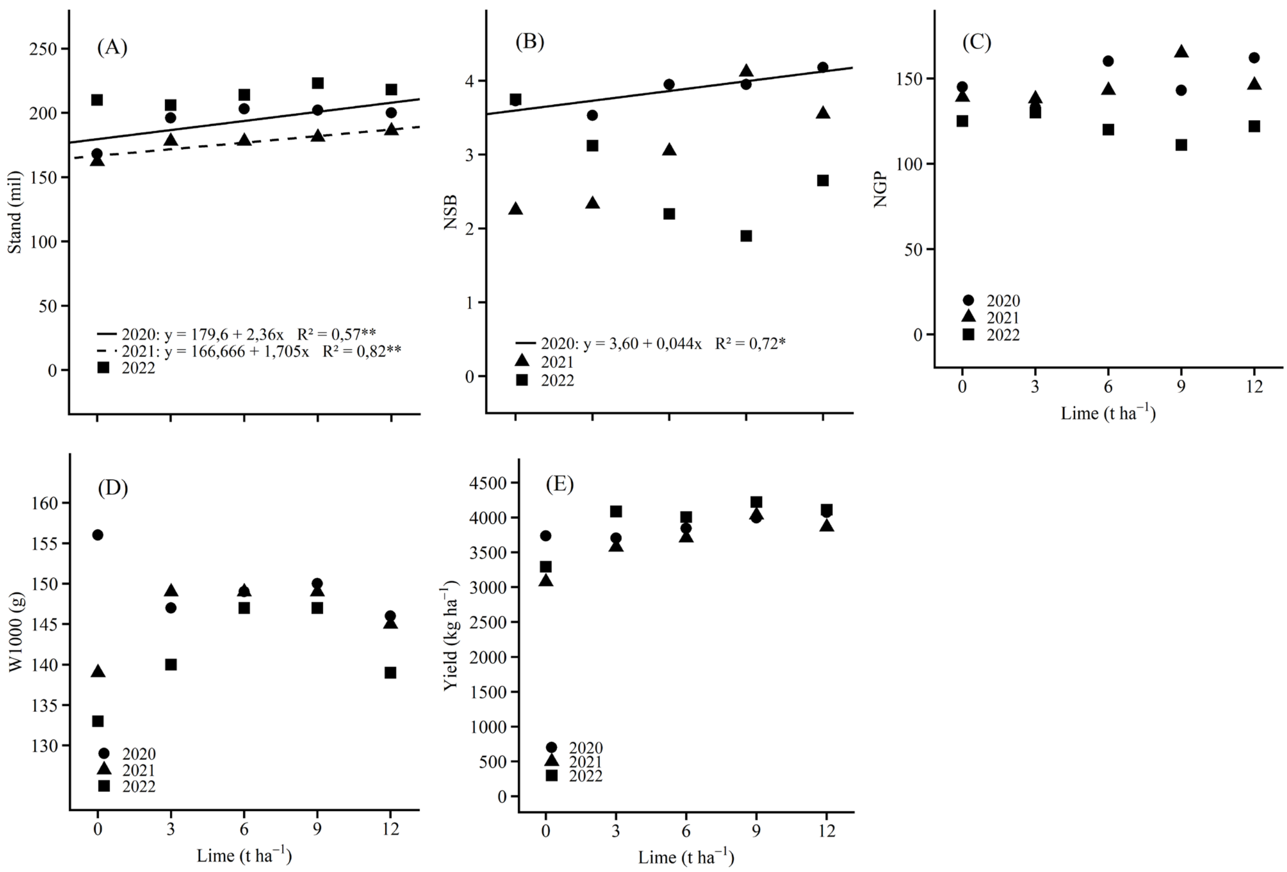


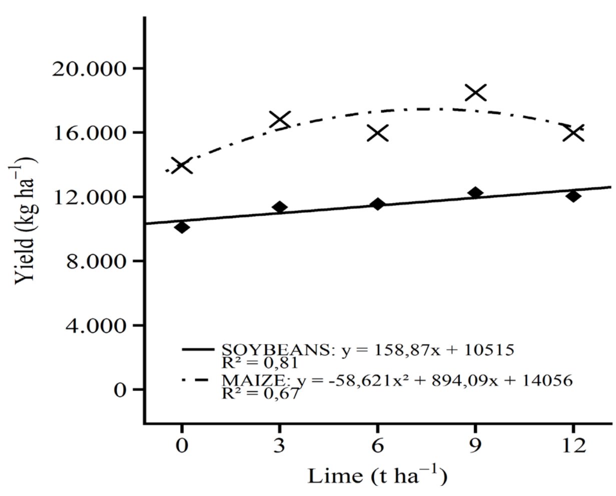
Figure 7 - Plant density (Stand), number of branches per plant (NSB), number of seeds per plant (NGP), thousand-seed weight (W1000) and soybean yield (Yield) in crops harvested in 2020, 2021 and 2022 due to lime application rates (t ha^{-1}) applied in April 2019 during the introduction of no-till farming in Marcêlandia municipality, Mato Grosso State, Brazil. ns: not significant; significant at $p < 0.05$; *: $p < 0.01$; **: $p < 0.001$***



after three years. Mean yield was 3.870 kg ha^{-1} in the first harvest (2020): soybeans produced 4.074 kg ha^{-1}, 130 kg ha^{-1} more than the study average; and 264 kg ha^{-1} more than the control, due to improved soil conditions. The 0.0 t ha^{-1} treatment produced 3,079 kg ha^{-1} in the 2021 harvest, whereas 4.034 kg ha^{-1} were harvested at the 9.0 t ha^{-1} application rate. The 0.0 t ha^{-1} treatment produced 3.294 kg ha^{-1} in the last harvest (2022), and the other treatments led to more than 4.000 kg ha^{-1}. The highest yield reached 4221 kg ha^{-1}, which showed the residual liming response, over time, and its effect at the highest application rates.

The observed yield at the highest rates exceeded the state averages: 3.587 kg ha^{-1}, 3.485 kg ha^{-1} and 3.735 kg ha^{-1}, respectively, in the 2020, 2021 and 2022 harvests. Several studies have shown yield increase in both soybeans and maize crops due to liming, mainly at higher-than-usual doses, due to improved soil fertility and residual effect, over time (Costa *et al*., 2016; Crusciol *et al*., 2016; Esper Neto *et al*., 2019; Moraes *et al*., 2023; Rodrighero; Barth; Caires, 2015).

Figure 8 - Cumulative yield (Yield) of soybeans and second-crop maize harvested in 2020, 2021, and 2022 due to lime application rates (t ha^{-1}) applied in April 2019 upon the introduction of no-till farming in Marcêlandia municipality, Mato Grosso State, Brazil



Maize yield increased in the last experimental year (Figure 9C). The other variables were not affected, despite the ~860 kg ha^{-1} (14.4 sc ha^{-1}) increase in grain yield when liming was compared with the 9.0 t ha^{-1} treatment (Table 3). There was severe impact of lack of rainfall on the first and second harvests because sowing was delayed due to management practices adopted by the farmer. New sites are typically the last to be sowed with soybeans in the region; therefore, the second-crop maize was also delayed, and it compromised the final yield. Mean yield 3.039 kg ha^{-1}, 3.513 kg ha^{-1} and 9.701 kg ha^{-1} was recorded in the 2020, 2021 and 2022 harvests, respectively. The state average recorded these harvests was 6.392 kg ha^{-1}, 5.625 kg ha^{-1} and 6.338 kg ha^{-1}, respectively. The positive result from 2022: mean yield of 9.701 kg ha^{-1}, is explained by sowing at the appropriate time and good water availability, which resulted in satisfactory yield. This scenario was further helped by improved soil fertility conditions after three years due to the lime reaction and to phosphorus addition to the soil.

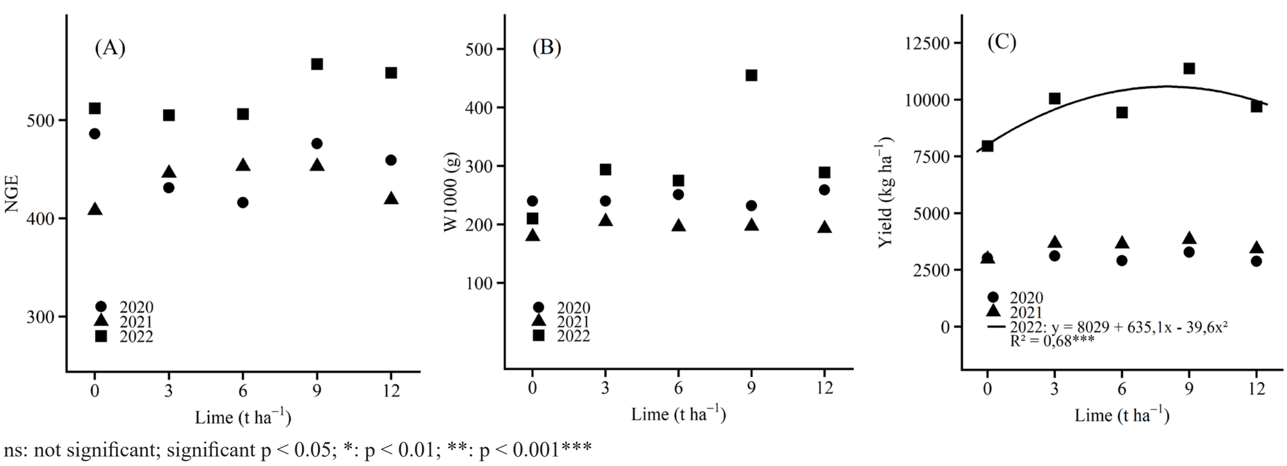
Cumulative maize yield showed significant effect and reached equation-adjusted value 17.45 t ha^{-1} at 8.0 t ha^{-1}, approximately 3.4 t ha^{-1} more than the control (Figure 8). Liming significantly improved soil nutrients availability, mainly P, Ca and Mg, besides reducing Al toxicity, and it improved root development and water use efficiency by the plants. This process directly and, often linearly, influences maize yield (Costa *et al*., 2016; Crusciol *et al*., 2016; Moraes *et al*., 2023; Rodrighero; Barth; Caires, 2015).

Lime application led to increased economic returns across all treatments in comparison to lack of soil liming. This finding highlighted this practice's feasibility in soybean and maize production systems in Northern Mato Grosso State, Brazil (Table 1). The 0.0 t ha^{-1} treatment generated net income of R$ 27,322.83, and this is a comparative baseline. There was net income increase at all rate levels after liming, although its association was nonlinear in both crops when the cumulative yield was analyzed.

The 3 t ha^{-1} treatment resulted in R$ 3,413.00 increase in comparison to the control, and this outcome pointed out high initial economic efficiency. Accordingly, partial soil acidity correction is already sufficient to achieve significant yield gains and financial return, with relatively low investment. Additional return was lower (R$ 2,592.42) at 6 t ha^{-1}, despite the increase in lime costs, and this finding suggests reduced investment marginal efficiency. The best economic performance was observed at the 9 t ha^{-1} treatment, as it led to net income of R$ 32,438.33 and to an increase of R$ 5,115.50 in comparison to the lime-free treatment.

Therefore, this rate was the most effective in maximizing economic returns over the three-year growing period. Thus, it is the economic optimum under the assessed conditions. On the other hand, the 12 t ha^{-1} dose reduced the net return (R$ 29,719.00) and only led to R$ 2,396.17 increase in comparison to the control, despite the higher investment. This result can be associated with Ca:Mg ratio imbalance caused by the exclusive use of dolomitic lime in combination with a likely slight shortage of micronutrients. On the other hand, the increased profitability is associated with soil acidity correction, reduced aluminum toxicity and higher nutrient availability, as these factors favor root development and crop yield.

Figure 9 - Kernels per ear (NGE), thousand-kernel weight (W1000) and maize yield (Yield) in the 2020, 2021 and 2022 crop seasons due to lime application rates in April 2019 during the introduction of no-till farming in Marcêlandia municipality, Mato Grosso State, Brazil



ns: not significant; significant $p < 0.05$; *: $p < 0.01$; **: $p < 0.001$***

Table 1 - Economic returns from soybean and maize crops during the three-year experimental time under different lime application rates. Marcelândia municipality, Mato Grosso State, Brazil

Treat. (t ha^{-1})	[1]Operational cost	[2]Cost of lime	[3]Grain returns	Net return	Difference
0	R$ 0.00	R$ 0.00	R$ 27.322.83	R$ 27.322.83	R$ 0.00
3	R$ 320.00	R$ 510.00	R$ 31.565.83	R$ 30.735.83	R$ 3.413.00
6	R$ 320.00	R$ 1.020.00	R$ 31.255.25	R$ 29.915.25	R$ 2.592.42
9	R$ 320.00	R$ 1.530.00	R$ 34.288.33	R$ 32.438.33	R$ 5.115.50
12	R$ 320.00	R$ 2.040.00	R$ 32.079.00	R$ 29.719.00	R$ 2.396.17

(1) -cost of incorporating an application (R$ 250.00 + R$ 70.00), (2) -cost of lime in the farm (R$ 170.00 per t), (3) -price per 60-kg bag of soybeans (R$ 100.00), price per 60-kg bag of corn (R$ 45.00) multiplied by the cumulative yield of each crop over three years

The hierarchical cluster analyses highlighted the clear separation of groups in response to the applied lime rates (Figures 10A and B). This separation was influenced by both soil chemical features and crop yield components ($p < 0.05$), which pointed towards close association between liming and plant development.

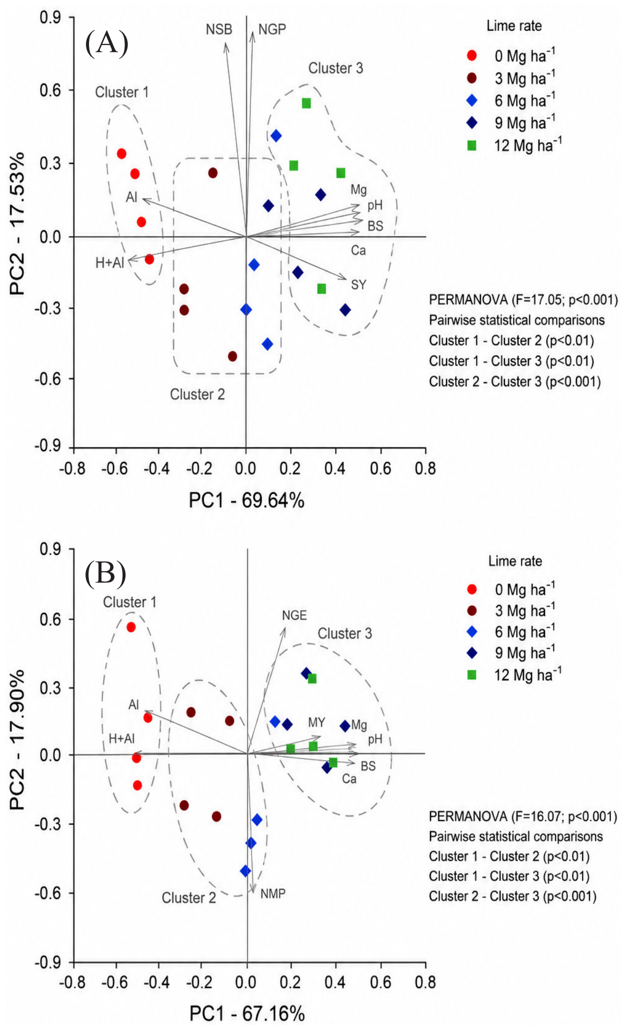
The principal component analyses explained more than 80% variability in the set of soil and crop variables. It summarized all the information into just two principal components for soybeans and maize, and identified the soil and plant features showing the highest variability in response to liming (Table 2).

Principal component 1 (PC1) accounted for 69% data variability in the analysis of soil fertility and soybean yield (Figure 10A) – it was represented by soil variables and soybean yield (Table 2). Principal component 2 (PC2), on the other hand, was represented by the number of branches per plant (NSB) and the number of seeds per plant (NGP). However, it played a less important role in defining the groups, because this component only accounted for 17% data variability (Figure 10A).

Cluster 1 comprised the plots without soil amendment. It was Featured by the highest aluminum content (0.26 $cmol_c\ dm^{-3}$) and potential acidity (5.82 $cmol_c\ dm^{-3}$) in the soil, as well as by lower BS values (20%), and pH (5.24), calcium (0.81 $cmol_c\ dm^{-3}$) and magnesium (0.47 $cmol_c\ dm^{-3}$) contents, as expected. These soil fertility conditions led to the lowest mean soybean yield - 3,370 kg ha^{-1} (Table 2).

Cluster 2 comprised the plots subjected to the 3 and 6 t ha^{-1} treatments. There was no difference in soil chemical features or soybean yield between these doses. These rates were not sufficient to precipitate all Al in the soil, but they increased soil pH, as well as Ca (1.52 $cmol_c\ dm^{-3}$) and Mg (0.89 $cmol_c\ dm^{-3}$) concentrations, and base saturation (32%), which resulted in soybean yield gain (3,635 kg ha^{-1}) (Figure 10 and Table 2). Nevertheless, it is clear that Ca and Mg levels were not ideal, and that the BS value remained

Figure 10 - Principal component analysis applied to soil chemical features in the 0 – 0.20 m layer under soybean (A) –maize (B) rotation in a no-till system. The pH, calcium (Ca^{2+}), magnesium (Mg^{2+}), aluminum (Al^{3+}) and potential acidity (H + Al), base saturation (BS), number of branches per plant (NSB), number of seeds plant (NGP), soybean yield (SY), number of maize plants per hectare (NMP), number of kernels per ear (NGE) and maize yield (MY). The dashed lines indicate the clusters identified through hierarchical analysis



low, which made it clear that applying rates ranging from 3 to 6 t ha^{-1} at the beginning of the of cultivation period in a degraded pasture site, even under deep incorporations, hid not achieve optimal soil correction after three crop seasons.

Cluster 3 comprised the treatments based on lime rates of 9 and 12 t ha^{-1}, without differences in soil fertility or soybean yield between these treatments (Figure 10 and Table 2). All aluminum in the soil was precipitated due to increase in the corrective dose from 6 to 9 t ha^{-1}. Calcium (Ca) content rose to 3.0 cmol$_c$ dm^{-3} and Mg to 2.0 cmol$_c$ dm^{-3}, and these are adequate values. There was Ca:Mg reduction due to the application of lime presenting high MgO content. In any case, BS values did not reach 70% in the 0 – 0.20 m soil layer; however, the 9 and 12 t ha^{-1} rates were enough to achieve further increase in soybean yield (4049 kg ha^{-1}) in comparison to the 3 and 6 t ha^{-1} rates.

Table 2 - Unstandardized soil, soybean and corn means due to each cluster, based on the hierarchical cluster analysis

Cluster	pH	Ca	Mg	Al	H + Al	BS	NSB	NGP	Y
		-------------------- cmol$_c$ dm^{-3} --------------------				%			kg ha^{-1}
Soybean									
1	5.24	0.81	0.47	0.26	5.82	20.09	3.36	138	3370
2	5.64	1.52	0.89	0.12	5.15	32.54	3.09	135	3635
3	6.15	2.95	2.049	0.00	3.18	61.37	3.21	139	4069
Maize									
1	5.24	0.81	0.47	0.26	5.82	20.09	46111	468	4655
2	5.66	2.06	1.19	0.03	4.67	41.36	49762	462	5590
3	6.20	2.96	2.12	0.00	3.04	63.06	46542	484	5632

[1]Means are followed by the confidence interval ($p \leq 0.05$). pH in water, Ca: calcium, Mg: magnesium, Al: aluminum, H + Al: potential acidity; BS: base saturation; NSB: number of branches per soybean plant; NGP: number of seeds per soybean plant; NMP: number of maize plants per hectare; NGE: number of kernels per ear; Y: soybean or maize yield

Table 3 - Eigenvalues, ratio of explained variance and correlation coefficients between soil features in the 0 – 0.20 m layer, principal components 1 and 2, and soybeans and corn features

Components	PC1	PC2	PC1	PC2
	Soybeans		Maize	
Eigenvalue	6.26	1.52	6.04	1.61
Explained variance (%)	69.64	17.52	67.16	17.89
Cumulative variance (%)	69.64	87.16	67.16	85.05
Variable[1]	Charge factor		Charge factor	
pH	0.97*	0.09	-0.96*	-0.00
Ca	0.95*	0.01	-0.95*	0.07
Mg	0.97*	0.11	-0.98*	-0.01
Al	-0.88*	0.14	0.88*	-0.28
H + Al	-0.97*	-0.10	0.97*	0.02
BS	0.99*	0.06	-0.99*	0.01
NSB/NMP	-0.17	0.84*	-0.05	0.89*
NGP/NGE	0.05	0,88*	-0.32	-0.83*
SY/MY	0.82*	-0.17	-0.64*	-0.10

[1]pH, calcium (Ca), magnesium (Mg), aluminum (Al) and potential acidity (H + Al), base saturation (BS), number of branches per soybean plant (NSB), number of seeds per soybean plant (NGP), soybean yield (SY), number of maize plants per hectare (NMP), number of kernels per ear (NGE) and maize yield (MY)

Multivariate analyses applied to maize showed similar patterns to those observed for soybeans (Figure 10B). PC1 also represented soil chemical features and corn yield, whereas PC2 represented the number of maize plants per hectare (NMP) and the number of kernels per year (NGE). Therefore, the groups were separated based on features correlated with PC1 (Table 3). The treatments were separated into three clusters: cluster 1 represented the control; cluster 2, the 3 and 6 t ha^{-1} treatments and cluster 3, the 9 and 12 t ha^{-1} ones. Overall, maize yield was low (5,292 kg ha^{-1}, on average) due to late sowing in the first two years of the study, which resulted in water stress for the crop. However, there were gains in maize yield, and it depended on the lime rates; maize yield rose from 4,655 kg ha^{-1} in cluster 1 to 5,643 kg ha^{-1} in cluster 3.

According to the multivariate analyses, variables like pH, Ca, Mg and base saturation were the most influential in separating the groups (Table 3), mainly Cluster 3, which corresponded to the highest lime rates (Figures 10A and 10B). These variables showed positive correlations with soybean and maize yield indicators, and this finding suggested that liming at rates up to 12 t ha^{-1} creates more favorable conditions for maize growth and yield in case of land clearing for agricultural purpose, although the achieved saturation level remains not ideal.

A similar study using lime applications up to 15 t ha^{-1} (Moraes *et al*., 2023) in soils presenting 40% to 50% clay content reached pH higher than 7.0 and base saturation higher than 80%, in some cases. Soybean, bean, and corn yields showed linear increase under this situation due to the rates applied over the three-year assessment. Studies using higher lime rates need to be conducted as effort to achieve BS values higher 70% and to assess their effects on soybean and maize yield. This calculation might allow establishing new liming recommendations. On the other hand, Cluster 1, which was associated with the lime-free plots, was featured by the negative influence of variables related to soil acidity (Al and H + Al), which, in their turn, underscored the liming relevance in mitigating these limiting factors.

The clear separation of groups based on principal component analysis results, in combination with the ranking of variable effects confirmed liming relevance as essential practice to manage tropical soils in no-till systems, mainly in degraded pasture sites conversion and soil profile formation, especially in soybean and maize rotations.

CONCLUSIONS

1. Converting degraded pasture into agricultural land by increasing lime doses applied at the end of the rainy season significantly changes the soil chemical features, which, in its turn, affects crop performance;
2. The cumulative yield of soybeans and maize over a three-year time proved significant for up to 12 t ha^{-1} lime application and it highlighted the feasibility of adopting higher-than-usual rates;
3. Lime application is economically viable in the assessed soybean-corn succession and the 9 t ha^{-1} rate maximizes the cumulative economic return.

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DATA AVAILABILITY STATEMENT

Data supporting the study results are available in [repository name] at: [URL or DOI], under the identifier [number/DOI].

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