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SOIL SCIENCE

Diagnose of soil fertility properties of a representative agricultural mesoregion in the Cerrado biome as affected by land use

TATIANE M. DE LIMA, MARCELA V. DA COSTA, REGINA MARIA Q. LANA, ATHOS GABRIEL G. NASCIMENTO, DIOGO CÉSAR P. DIAS & BRUNO T. RIBEIRO

Abstract: In Brazil, most of cereal production is concentrated in the Cerrado which is characterized by poor soils. Thus, the soil fertility management is important for suitable use of Cerrado's soils. After 40 years of increasing use of Cerrado for agricultural purposes, this work aimed to evaluate the soil fertility of a representative area known as *Triângulo Mineiro* and *Alto Paranaíba* (TMAP) mesoregion. Different land uses from 126 farms were selected for soil sampling and assessed the following properties: pH; exchangeable Al^{3+}, Ca^{2+}, Mg^{2+}; available P, K^{+}, S, B, Fe, Cu, Mn, and Zn; soil organic matter (SOM); and cation exchange capacity (CEC) effective and potential at pH 7.0. Land uses improved the soil fertility properties compared to native Cerrado vegetation, except planted forests. The pH increased and Al^{3+} was neutralized, however, satisfactory contents of Ca^{2+} and Mg^{2+} were not reached. CEC is still considered low to medium, since SOM was not significantly increased. Available P, S, Fe, Mn, Zn, and Cu contents increased, being considered satisfactory. In general, our findings suggest that the nutrients can be considered adequate for crop production and sustainability. However, continuous monitoring for maintenance of soil fertility and adoption of best management practices are needed.

Key words: soil health, soil quality, soil fertility, tropical crops, tropical soils.

INTRODUCTION

Currently, most of agricultural activities in Brazil is concentrated in the Cerrado biome (Lopes & Guilherme 2016). In Minas Gerais State, there is an important mesoregion known as *Triângulo Mineiro* and *Alto Paranaíba* (TMAP) covering approximately 91,000 km^2. The TMAP region comprises 27% of the Cerrado area of Minas Gerais State (IBGE 2018) being considered the most developed agricultural region of the state, adopting modern technology, high yields, and great diversification of agricultural products (Landau et al. 2018).

TMAP region was pioneer in the agriculture developed in the Cerrado due to three main characteristics: edaphoclimatic conditions, strategic location, and infrastructure for transport (Chelotti & Rosolen 2014). After 40 years of increase agricultural use, it is estimated that 75% of the natural vegetation of TMAP was converted to crop-livestock-forestry systems (Sano et al. 2010). In general, approximately 22% of native Cerrado vegetation was cleared in the last three decades (Pompeu et al. 2024). Currently, TMAP concentrates the agricultural production of the State of Minas Gerais and it is responsible for 52% of the exportation values of agriculture products (IBGE 2018).

The agricultural land use in TMAP was developed mainly on Latosols (Oxisols per Keys to US Soil Taxonomy; Soil Survey Staff 2014), with flat to gentle undulating relief that favors agricultural mechanization (Lopes et al. 2012). These soils are highly weathered and present low natural fertility besides having high acidity and aluminum saturation, low organic matter (SOM) content, low cationic exchange capacity (CEC), and low nutrient availability (Lopes & Guilherme 2016). Therefore, the suitable use of soils for agricultural production in the TMAP region necessarily depends on the continuous use of soil amendments and fertilizers (Resende et al. 2016, Lopes & Guilherme 2016).

Over the last 40 years, substantial research works were conducted, especially on soil fertility, aiming to propose strategies and technologies for the sustainable use of the Cerrado's soils (Lopes & Guilherme 2016). It is important to notice that, currently, modern agriculture no longer has been focusing only on productivity and sustainability. Soil and food security are also premises of modern and sustainable agriculture (Pozza & Field 2020). Thus, a general diagnose of the soil fertility status in the main agricultural regions of the country, such as TMAP, it is timely important and will contribute to the advancement of Brazilian agriculture. Such diagnose will point out, after years of intensive use, the changes in soil fertility properties, potentialities, and limitations that may still exist.

The present work was conducted to obtain a general survey of soil fertility in TMAP areas under different uses. The specific objectives were to: (i) compare the soil fertility conditions with native Cerrado vegetation having as reference the historical inventory performed by Lopes (1975) and Lopes & Cox (1977); and (ii) compare soil fertility properties of different areas under different land uses in the TMAP.

MATERIALS AND METHODS

Description of the study area and soil sampling

The selected area for this study is located in Minas Gerais State, known as *Triângulo Mineiro* and *Alto Paranaíba* (TMAP) mesoregion (Figure 1). TMAP is totally located in the Cerrado Biome (Figure 1), and in four important rivers basins: *Araguari* River Basin (21,500 km^2), *Alto Paranaíba* River Basin (22,200 km^2), *Baixo Paranaíba* River Basin (26,900 km^2) and *Baixo Rio Grande* Basin (18,700 km^2).

In the *Araguari* River Basin, the climate varies between Cwb and Cwa according to the Köppen climatic classification. In the other basins, the climate is predominantly Aw. Based on the soil map of the Minas Gerais State (FEAM 2010), shape files (IBGE 2024; IDE-SISEMA 2024), and after field observations, the soils in the studied areas and sampling sites (Figure 1) were classified as dystrophic Red Latosols and dystrophic Red-Yellow Latosols per Brazilian System of Soil Classification (Santos et al. 2018). Considering all sampling sites, the mean altitude was 836 m, varying from 552 to 1,110 m. The mean slope was 5%, varying from 1 to 13%. The altitude was measured using a handheld GPS Garmin 64SX and the slope using a clinometer.

As shown in Figure 1, different land uses (cereals, coffee, planted forests, sugarcane, pasture, horticulture, and native vegetation) from 126 representative farms were selected. Cereals (corn, soybean, sorghum and sunflower) represented 37% of sampling sites; coffee (8%); planted forests (eucalyptus, pine, and rubber tree) (8%); sugarcane (8%); pasture (25%); horticulture (12%); and native Cerrado as reference (4%). The definition of sampling sites was also performed considering the proximity to the soils studied by Lopes (1975) and Lopes & Cox (1977) still under native Cerrado vegetation. Soil sampling sites comprise 16 municipalities in

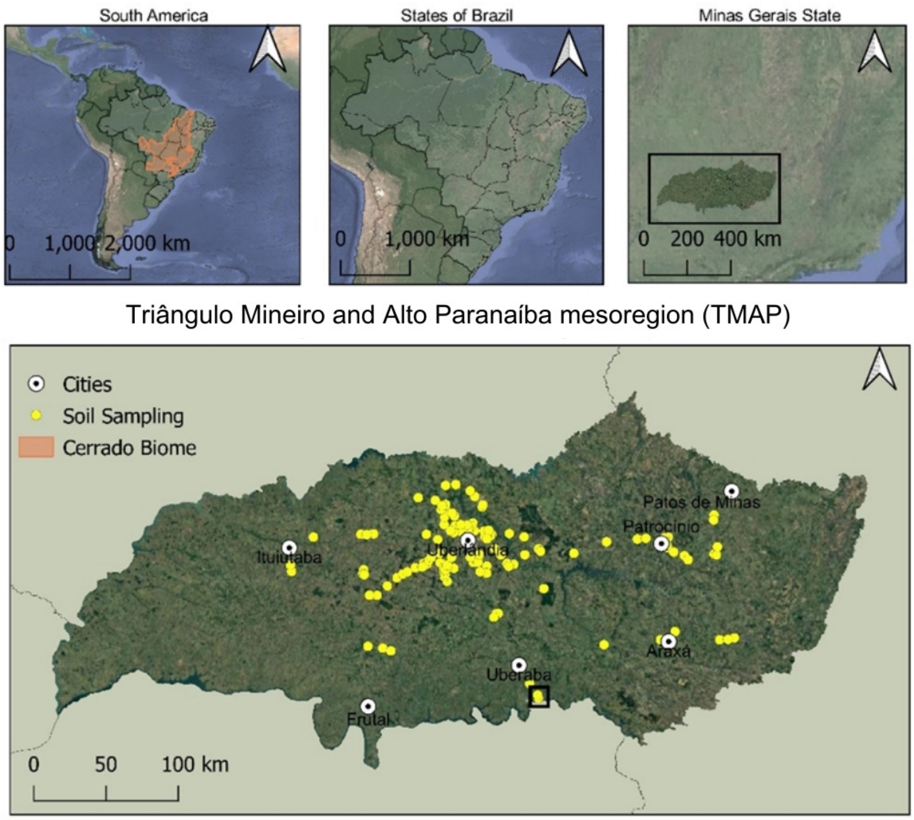

Figure 1. **Location of the study area and sampling points in the Triângulo Mineiro and Alto Paranaíba region – TMAP.**

Minas Gerais State: *Uberlândia*, *Araguari*, *Araxá*, *Ibiá*, *Patrocínio*, *Iraí de Minas*, *Tupaciguara*, *Monte Alegre*, *Ituiutaba*, *Prata*, *Comendador Gomes*, *Nova Ponte*, *Indianópolis*, *Serra do Salitre*, *Patos de Minas*, and *Perdizes*.

In each sampling site (Figure 1), two composite samples from 0-20 cm layer were collected, totalizing 252 soil samples. Each composite sample (approximately 200 m apart) was formed by mixing 10 single samples. The sampling procedures followed technical recommendation for each crop as described in Cantarutti et al. (2007). After field sampling, the samples were air-dried, passed through a 2 mm sieve and stored for further analyses.

Physical and chemical characterization

The following soil properties were determined: pH in water; potential acidity (H + Al); exchangeable Ca^{2+}, Mg^{2+}, and Al^{3+}; available P, K^{+}, S-SO_4^{2-}, Zn, Cu, B, Fe and Mn; effective and potential cation exchange capacity (CEC1 and CEC2, respectively); sand, silt, and clay contents; organic matter; and remaining phosphorus (P-rem). In the laboratory, each composite sample (n = 252) was analyzed in duplicate, totalizing 504 observations. The analytical procedures followed the Handbook for Soil Analysis in Brazil (Teixeira et al. 2017), described as follow.

The pH in water was determined by preparing a soil suspension in water (soil:water slurry 1:2.5 *v/v*), which was shaken (orbital shaker) for 15 minutes and let rest for 1 hour until the pH measurements. The potential acidity (H+Al) was determined by SMP buffer solution method. For that, 10 cm^3 of TFSA were placed in 50 mL plastic pots containing 25 mL of 0.01 mol L^{-1} $CaCl_2$ and 5 mL of SMP buffer solution. The suspension was shaken for 15 minutes (220 rpm) using an orbital shaker. After stirring, the suspension was let to rest for one hour and then the equilibrium pH was taken to estimate H + Al concentration.

The exchangeable cations (Ca^{2+}, Mg^{2+}, and Al^{3+}) were extracted with 1.0 mol L^{-1} KCl solution (soil:solution ratio 1:10 *v/v*). Using a 250 mL Erlenmeyer flask, the soil suspension was shaken for 15 minutes using an orbital shaker and let to rest overnight (16 h). In the filtered supernatant, Ca^{2+} and Mg^{2+} were quantified by atomic absorption spectrometry with a flame atomizer, and Al^{3+} by titration with 0.025 mol L^{-1} NaOH solution. Using the same extraction procedure, the available K^{+}, P, Cu, Zn, Mn, and Fe were extracted with Mehlich-1 solution. K^{+} was quantified using a flame photometer, and P by molybdenum blue colorimetric method. P-resin was determined according to Raij et al. (1994). Micronutrients (Cu, Zn, Mn, and Fe) were quantified by atomic absorption spectrometry with a flame atomizer. B was determined by the hot water method, using 1.25 g L^{-1} $BaCl_2$ solution (soil:solution ratio 1:2), with microwave heating for 4 min at maximum power (Raij et al. 2001). In the obtained extract, B was quantified by colorimetry in Azomethine-H using a spectrophotometer at 420 nm (Raij et al. 2001). The $S\text{-}SO_4^{2-}$ was determined by turbidimetry (Vitti & Suzuki 1978). Soil organic matter (MOS) was determined by colorimetry (Nelson & Sommers 1996), after oxidation with 0.167 mol L^{-1} $K_2Cr_2O_7$) acid solution. Soil texture was determined by the hydrometer method (Gee & Bauder 1986).

After chemical characterization, the following soil fertility indicators were calculated: CEC1 as a sum of Ca^{2+}, Mg^{2+}, K^{+}, and Al^{3+}; CEC2 as a sum of Ca^{2+}, Mg^{2+}, K^{+}, and H+Al; sum of bases (SB) as Ca^{2+} + Mg^{2+} + K^{+}; base saturation on CEC1 (BSP) as SB/CEC1 (%); and Al saturation on CEC1 as Al^{3+}/CEC1.

Remaining phosphorus (P-rem) was determined as the phosphorus concentration in the equilibrium solution after shaken with 0.01 mol L^{-1} $CaCl_2$ solution containing 60 mg L^{-1} of P (ratio 1:10) (Alvarez et al. 2000). The P in the equilibrium solution was determined by the colorimetric method in acid ammonium molybdate solution. P-rem represents the P sorption capacity (high P-rem, low P sorption), and it has been employed in Brazil to assess the availability of P and $S\text{-}SO_4^{-2}$ in tropical soils (Alvarez et al. 2000).

Based on exchangeable Ca^{2+}, Mg^{2+}, Al^{3+}, and CEC2, the following ratios were also assessed: Ca/Mg, Ca/K, Mg/K, Ca/CEC2 (%), Mg/CEC2 (%), and K/CEC2(%). As reference, the following intervals were considered adequate (Bear & Toth 1948, Adams & Henderson 1962, Liebhardt 1981: Ca/Mg (6:1 to 10:1); Ca/K (5:1 to 10:1); Mg/K (1:1 to 2:1); Ca/CEC2 (65-85%); Mg/CEC2 (4-12%); and K/CEC2 (2-5%).

Statistical analyses

Descriptive statistics (minimum, maximum, mean, median, and standard deviation), normality (Kolmogorov-Smirnov) and asymmetry (Skewness) tests were performed. Afterward, frequency distributions were made for each soil property. Intervals (classes amplitude) for each soil property were defined as the same classes commonly used in soil fertility interpretation for Brazilian agricultural soils (very low, low, medium, high, and very high). For each soil property, agricultural land uses were compared using box-plots including the critical levels as reference. Statistical analyses and graphics were made using R software version 4.2.0 (R Core Team 2022), and Sigma Plot software version 13.2 (Systat Software Inc. 2006).

RESULTS AND DISCUSSION

Soil reaction

The soil pH ranged from 3.8 to 7.6 (Table I). Markedly, most of samples had pH in water classified as low (from 4.5 to 5.5) and medium (5.5 to 6.5) (Figure 2a). Approximately 44% of soil samples had pH in water considered adequate for plant growth (from 5.5 to 6.5). This can be attributed to suitable and periodical use of liming in Cerrado agricultural soils (Yamada, 2005). Only 11% had pH values higher than 6.5, probably due to excessive liming that might contributes to undesirable unavailability of soil micronutrients (Vitti & Trevisan 2000, Raij 2001). In soil samples from native Cerrado sampled by Lopes (1975) and Lopes & Cox (1977) approximately 40 years ago, most pH values ranged from 4.8 to 5.2, and 48% of samples were acidity (pH < 5.0) (Lopes & Guilherme 2016). The changes found herein reflect the gradual adoption of liming over the time. As a consequence of increasing pH in water, the exchangeable acidity (Al^{3+}) were substantially reduced (Figure 2b). The well-known consistent relationship between soil pH and exchangeable Al^{3+} was demonstrated by Sade et al. (2016). Al^{3+} concentration is relevant only in soils with pH below 5.0. Compared to native Cerrado soils (Lopes 1975, Lopes & Cox 1977), which contain predominantly Al^{3+} higher than 0.25 $cmol_c\ dm^{-3}$ (Lopes & Guilherme 2016), herein most of samples (almost 60%) had Al^{3+} lower than 0.2 $cmol_c\ dm^{-3}$, being classified as very low. As mentioned by Lopes & Guilherme (2016) the absolute concentration of Al^{3+} is not a concern. The most important and undesirable is its high percentage on cation exchange capacity in highly-weathered tropical soils.

In native Cerrado condition, most Al^{3+} saturation on CEC1 ranged from 50 to 80% (Lopes & Cox 1977, Lopes & Guilherme 2016). As can be seen in Figure 2d, markedly, most of soil samples (> 80%) from TMAP region had Al^{3+} saturation on CEC1 lower than 15%, being classified as very low. Summarizing the importance of liming in Cerrado tropical soils for agricultural purposes (Lopes & Guilherme 2016), the pH in water was mainly correlated with BSP in the TMAP region (Figure 3). It is worth noticing that Cerrado soils, planted forest areas and part of pasture and cereal crops remain in poor soils with the lowest pH values, highest Al^{3+} and coarser texture (Figures 3, 5a, 5c and 5d).

Native cerrado soils are naturally acidic due to intense leaching of bases (Lopes & Cox 1977, Lopes et al. 2012, Lopes & Guilherme 2016). Therefore, pH changes in agricultural areas primarily occur due to liming practices, fertilization (especially nitrogen fertilizers), decomposition of organic matter, and the consumption and/or leaching of bases in the soil (Brady & Weil 2013). The reduction of pH increases exponentially the exchangeable Al^{3+} which after its hydrolysis contributes to soil acidity (Sá et al. 2010, Brady & Weil 2013, Sade et al. 2016). Thus, the use of limestone is essential for suitable agricultural use of Cerrado soils (Lopes & Guilherme 2016). In addition to Ca and Mg fertilization and pH correction, both limestone and gypsum practices have been promoting the Al neutralization. Also, limestone works as conditioner of many chemical and physical soil attributes (Fageria & Baligar 2008, Sade et al. 2016).

Although the liming practice is undoubtedly beneficial for Cerrado agricultural soils (Lopes & Guilherme 2016), the movement of $CaCO_3$ through the soil profile is too low. Thus, the incorporation of corrected lime doses at deeper depths through plowing and harrowing is always desirable. Further studies to assess the status of soil fertility conditions in detail at different depths are timely relevant. Currently, the reduction of Al^{3+} availability and increase of Ca^{2+} content at deeper depths has been reached via gypsum application as discussed later herein.

As observed for pH in water, most potential acidity (H+Al) values of samples were classified as low to medium (Figure 2c). It was also found that 45% of the areas exhibited low potential acidity (< 2.5 $cmol_c\ dm^{-3}$); 43% ranged from 2.5 to 5.0

Table I. Descriptive statistics of attributes of soil samples from Triângulo Mineiro and Alto Paranaíba mesoregion, Cerrado biome, Brazil.

Attribute	Min.	Max.	Mean	Median	CL	s.d	Skewness	Kolmogorov-Smirnov
pH in water	3.8	7.6	5.6	5.7	5.5-6.0	0.7	0.1	$0.1^{n.s}$
Al^{3+}(cmol$_c$ dm^{-3})	0.0	1.9	0.1	0.0	1.0	0.3	3.1	$0.3^{n.s}$
H+Al (cmol$_c$ dm^{-3})	0.7	11.8	3.0	2.7	5.0	1.6	1.4	$0.1^{n.s}$
P-M1 (mg dm^{-3})	0.7	299.2	29.1	12.0	*	41.8	2.9	$0.2^{n.s}$
P-rem (mg dm^{-3})	1.0	13.85	7.8	8.0	-	3.6	- 0.2	$0.0^{n.s}$
S-SO_4^{2-} (mg dm^{-3})	4.0	243.0	19.3	12.0	*	28.6	5.1	$0.3^{n.s}$
K^+ (mg dm^{-3})	8.0	942.5	99.5	69.3	70.0	112.7	4.0	$0.2^{n.s}$
Ca^{2+} (cmol$_c$ dm^{-3})	0.1	6.8	2.3	2.1	2.4	1.5	0.7	$0.1^{n.s}$
Mg^{2+} (cmol$_c$ dm^{-3})	0.0	3.4	0.7	0.6	0.9	0.5	2.1	$0.1^{n.s}$
SB (cmol$_c$ dm^{-3})	0.1	10.2	3.2	2.9	3.6	2.0	0.8	$0.1^{n.s}$
CEC1 (cmol$_c$ dm^{-3})	0.5	10.2	3.3	3.0	4.6	1.9	1.0	$0.1^{n.s}$
CEC2 (cmol$_c$ dm^{-3})	1.6	16.5	6.2	6.1	8.6	2.6	0.7	$0.1^{n.s}$
BSP (%)	1.0	89.8	48.8	51.0	60.0	19.5	-0.4	$0.1^{n.s}$
m (%)	0.0	94.0	9.2	0.0	50.0	19.4	2.7	$0.3^{n.s}$
SOM (g kg^{-1})	7.5	47	21	21	40.0	8	0.5	$0.1^{n.s}$
B (mg dm^{-3})	0.1	1.8	0.3	0.2	0.6	0.2	3.6	$0.2^{n.s}$
Cu (mg dm^{-3})	0.4	25.6	3.6	2.0	1.2	4.1	2.9	$0.2^{n.s}$
Fe (mg dm^{-3})	3.0	429.8	50.3	43.9	30.0	43.4	5.6	$0.2^{n.s}$
Mn (mg dm^{-3})	3.1	224.3	32.6	19.2	8.0	32.8	2.2	$0.2^{n.s}$
Zn (mg dm^{-3})	0.0	25.7	4.6	3.2	1.5	4.5	1.8	$0.2^{n.s}$
Clay (g kg^{-1})	150	750	411	350	---	202	0.17	$0.2^{n.s}$

CL: critical level in the soil (Alvarez et al. 1999); s.d.: standard deviation; * CL interpretation depends on the clay content and/or P-rem.; ns: non-significant.

cmol$_c$ dm^{-3}; and only 12% showed high potential acidity. H+Al reflects the soil buffering capacity being influenced mainly by the organic matter content in tropical soils (Brady & Weil 2013, Lopes & Guilherme 2016). A significant difference among land use was not observed for H+Al (Figure 5b), except for Cerrado soils which presented the lowest values.

CEC1 ranged from 0.5 to 10.2 cmol$_c$ dm^{-3} (Table I). These values are very similar to those found for Cerrado native soils (0.4 to 8.1 cmol$_c$ dm^{-3}) (Lopes & Guilherme 2016). Most of samples had low CEC1 (0.8 to 2.3 cmol$_c$ dm^{-3}) and medium (2.3 to 4.6 cmolc dm^{-3}) (Figure 2e). For native Cerrado soils, most of samples (> 70%) had CEC1 < 1.5 cmol$_c$ dm^{-3}. Most of agricultural soils from TMAP region (~ 60%) had CEC2 classified as medium, ranging from 4.3 to 8.6 cmol$_c$ dm^{-3} (Figure 2f). Compared to native Cerrado soils (Lopes & Cox 1977), the desirable increase in CEC is reached through liming and sustainable land use to gradually increase soil organic matter. Again, the land use effect did not have a prominent effect on CEC (Figures 5e and 5f), except for Cerrado soils which presented the lowest values of effective cation exchange capacity (Figure 5e).

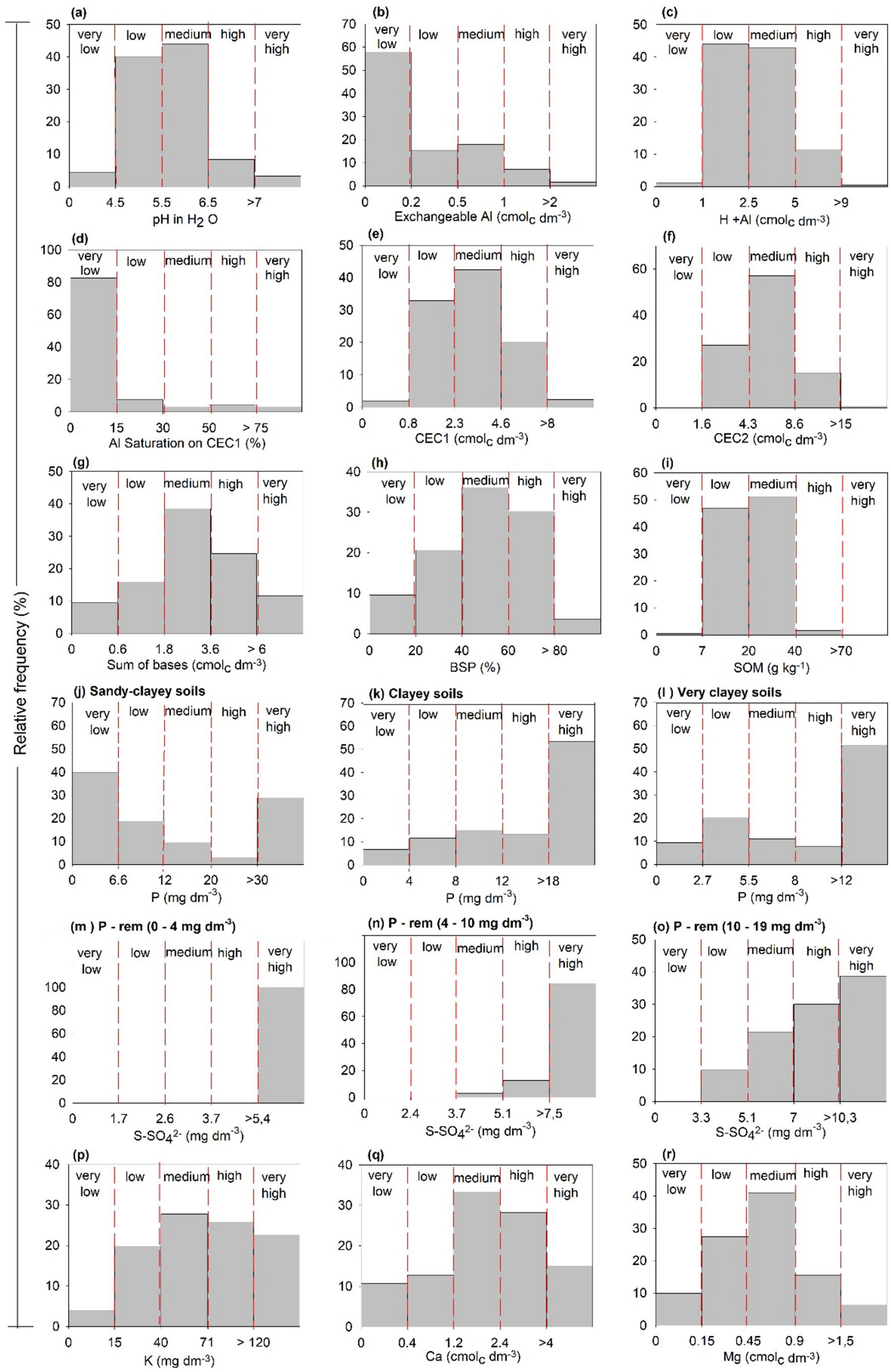

Figure 2. Frequency distribution for pH in water (a), exchangeable Al^{3+} (b), H+Al (c), Al saturation on CEC1 (d), CEC1 (e), CEC2 (f), sum of bases (g), base saturation percentage (BSP) (2), SOM (i), P Mehlich-1 (j, k, l), S-SO_4^{2-} (m, n, o), available K^+ (p), exchangeable Ca^{2+} (q), and exchangeable Mg^{2+} (r) of agricultural soils in the Triângulo Mineiro and Alto Paranaíba mesoregion. The critical level mentioned in the text corresponds to the upper limit of the medium class (Alvarez et al. 1999).

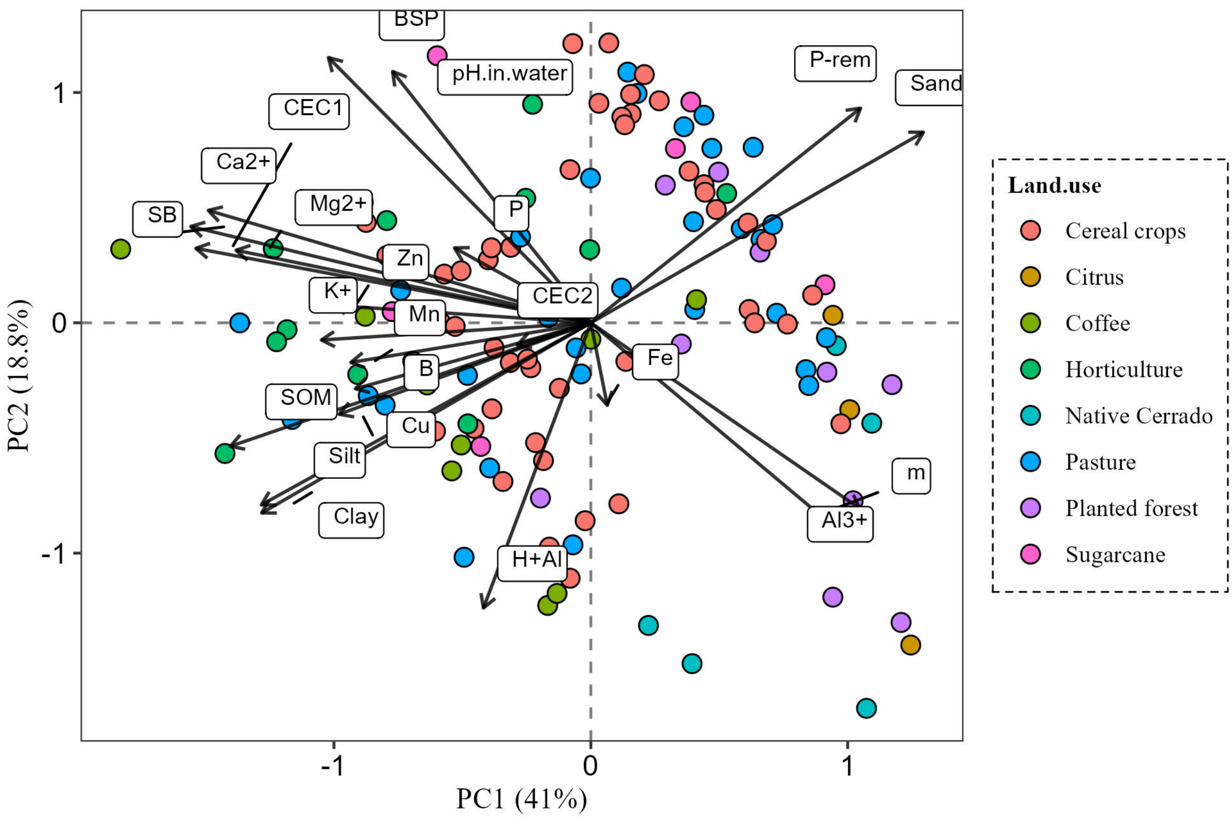

Figure 3. Principal component analysis (PCA) of fertility properties of soils from Triângulo Mineiro and Alto Paranaíba mesoregion, Cerrado biome, Brazil, influenced by land use.

Summarily, in the TMAP region, most planted forests had pH values, Al^{3+} content, and aluminum saturation similar to native Cerrado soils (Figure 3). Some cereal crops, citrus, and pastures areas are still growing in low fertility conditions. All other land use types, including some pastures, are associated with the best soil fertility conditions (Figures 3 and 5).

Soil organic matter

Most samples (98%) had low and medium contents of organic matter (Figure 2i). Considering these samples, 51% and 47% had medium and low contents, respectively. These results suggest that the land use practices adopted in the study area have not yet been able to increase soil organic matter content to satisfactory contents (Figures 2i and 5i). In Cerrado soils under native vegetation (Lopes & Cox 1977), organic matter content ranged from 7 to 60 g kg^{-1}, with median of 22 g kg^{-1} (Lopes & Guilherme 2016). Significant increases in soil organic matter content were not achieved yet regardless the land use (Figure 5i). Furthermore, levels above the critical threshold (40 g kg^{-1}) were found in only 2% of the samples. These few samples came from some horticulture and pasture areas (Figures 3 and 5). The highest soil organic matter content is reasonably attributed to frequent organic fertilization from different manures (Sato et al. 2012, Souza et al. 2015).

TMAP region is characterized by edaphoclimatic conditions that favor microbial activity and organic matter decomposition, making its accumulation in the soil difficult (Bustamante et al. 2006, Carvalho et al. 2010,

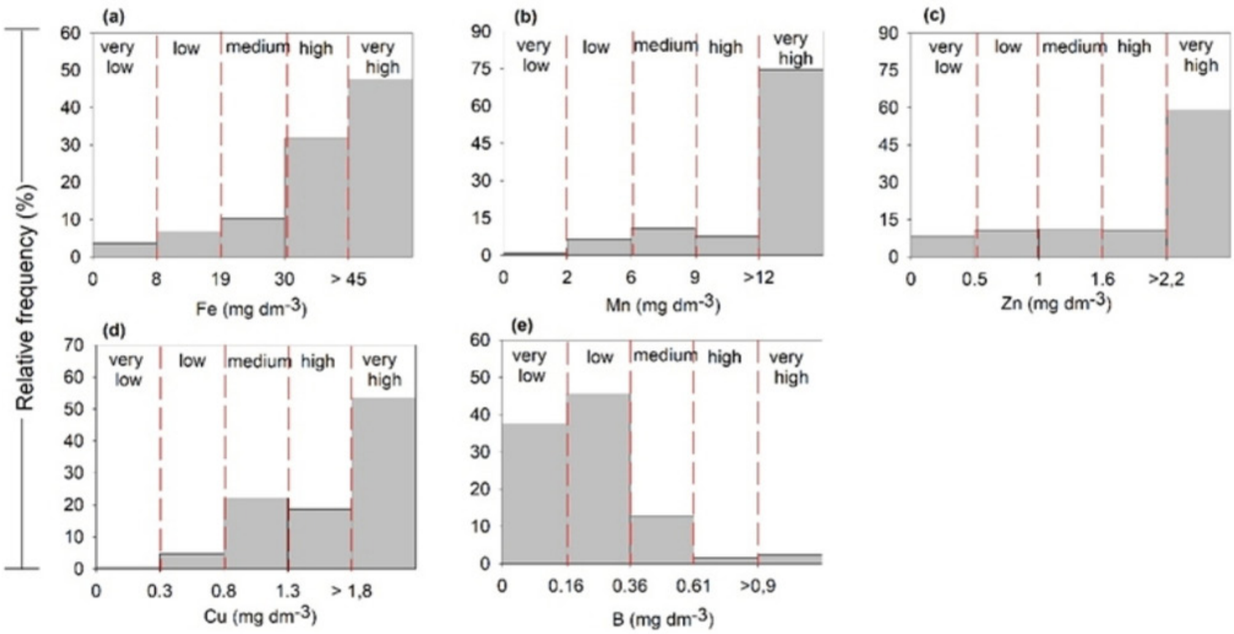

Figure 4. **Frequency distribution for Fe (a), Mn (b), Zn (c), Cu (d) and B (e) available from the soils of the Triângulo Mineiro and Alto Paranaíba regions. Critical level considered: upper limit of the average interval (Alvarez et al. 1999).**

Oliveira et al. 2015, Sá et al. 2010). Hence, the accumulation of crop residues in no-till system is hampered (Bustamante et al. 2006, Guareschi et al. 2012). It is estimated that the decomposition rate of soil organic matter in tropical soils is 10 times higher than temperate soils (Costa et al. 2014). Thus, increase of soil organic matter in Cerrado agricultural soils is considered one of the main challenges (Pacheco et al. 2008).

The improvement of soil fertility of Cerrado soils requires, undoubtedly, the increase of organic matter by the adoption of conservation practices such as minimum and no-tillage (Resende et al. 2016), forest-crop-livestock systems (Salton et al. 2011), and crop rotation (Gmach et al. 2018, Soltangheisi et al. 2018). One of the most important contribution of organic matter in tropical soils is related to its effect on CEC. It is estimated that up to 90% of CEC is due to soil organic matter (Canellas et al. 1999, Alvarez-Puebla et al. 2005, Bronick & Lal 2005, Bayer & Mielniczuk 2008). In some regions and/or experimental conditions, soil organic matter has been increased as affected by different management practices, such as: crop rotation (Silva et al. 2006, Soltangheisi et al. 2018, Zotarelli et al. 2012); crop-livestock system (Crusciol et al. 2010, Loss et al. 2011); manures application (Ghosh et al. 2011, Abdala et al. 2012); and no-tillage (Bezerra et al. 2015, Moraes et al. 2016, Loss et al. 2011, Sá et al. 2010). The adoption of no-tillage system in the Cerrado biome has been considered the most important strategy to increase soil organic matter content and, consequently, conditioning many other physical, chemical and biological attributes (Lopes & Guilherme 2016).

Macronutrients

Available phosphorus

Figures 2j to 2l show the available P extracted with Mehlich-1 (P-M1) solution interpreted based on soil texture (sandy-clayey, clayey, and

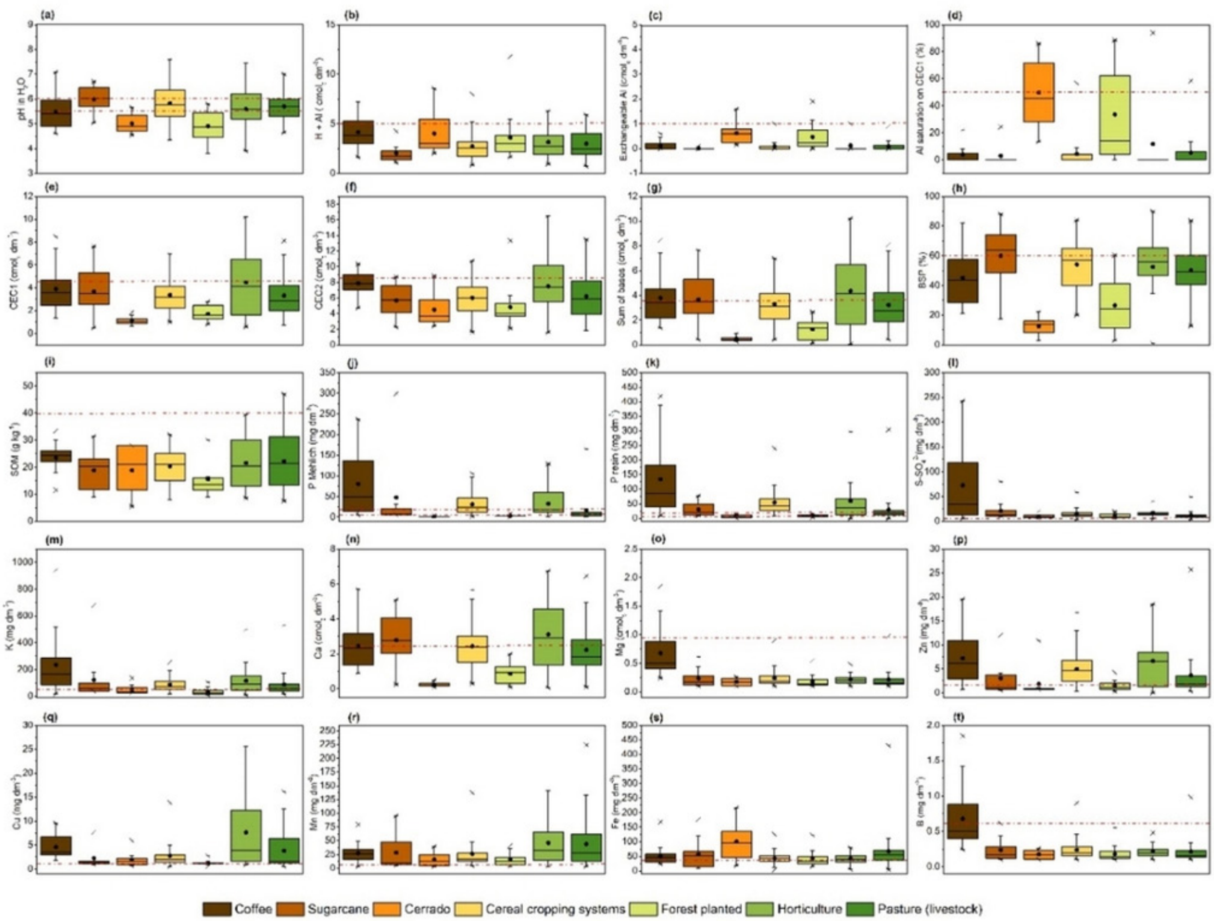

Figure 5. ffect of land use on pH water (a), H + Al (b), Exchangeable Al (c), Al saturation in CEC1 (d), CEC1 (e), CEC2 (f), Sum of bases (g), BSP (h), SOM (i), P mehlich-1 (j), P resin (k), S-SO4-2 (l), K (m), Ca (n), Mg (o), Zn (p), Cu (q), Mn (r), Fe (s) and B (t) of agricultural soils in the Triângulo Mineiro and Alto Paranaíba region. Critical level considered: upper limit of the average interval (Alvarez et al. 1999).

very clayey soils). Considering the full dataset, the median value for available P-M1 was 12.0 mg dm^{-3}, ranging from 0.7 to 299 mg dm^{-3} (Table I). This result shows that phosphate fertilization management in long term increased the P content and availability in agricultural soils of TMAP, since native areas before agricultural used presented available P varying from 0.1 to 16.5 mg dm^{-3} (Lopes & Cox 1977, Lopes & Guilherme 2016). However, compared to native Cerrado soils studied herein a significant increase in the P availability (P-M1 and P-resin) (Figures 5j and 5k, respectively) was observed only for coffee areas (mainly) followed by horticulture and cereal crop systems (Figures 5j and 5k). Continuous application of P fertilizers in quantities higher than the annual removal by crops contributes to build-up a P reservoir through the years, increasing available P content even in soils with high P fixation capacities (Ghosh et al. 2011, Abdala et al. 2012, Barrow & Debnath 2014, Roy et al. 2017). In addition, P adsorption in Cerrado soils decreases with the saturation of adsorption sites (Roy et al. 2017). As presented in Figure 3, available P was associated to the highest pH in water, BSP and CEC. Despite the increase of available P compared to native Cerrado (Lopes & Cox 1977), in sandy-clayey soils, only 32 % of samples showed available P superior to the critical level (Figure 2j). In clayey and very clayey soils (Figures 2k and 2l), 67 and 59 % of samples presented available P superior to the critical level, respectively. Some management practices has been contributing to reduce P adsorption in tropical soils increasing its availability such as: pH correction through liming application (Souza et al. 2006), no-tillage, crop rotation and manure application (Ghosh et al. 2011, Abdala et al. 2012, Groppo et al. 2015, Rodrigues et al. 2016, Soltangheisi et al. 2018).

Available K^+ and exchangeable Ca^{2+} and Mg^{2+}

The contents of exchangeable Ca^{2+} and Mg^{2+} have not yet been elevated to satisfactory levels in most areas of TMAP (Table I). Fifty-seven percent of the areas showed exchangeable Ca contents below the critical level (Figure 2q), and 79% had unsatisfactory contents of Mg (Figure 2r). Most of samples had sum of bases and BSP (%) below the critical limits (Figure 2g and 2h). For Mg, all land uses presented values below the critical limit (Figure 5o). Also, sum of bases and BSP (%) varied significantly among land uses (Figures 5g, 5h and 5n, respectively). Ca and Mg may be limiting the development of plants grown in the TMAP region, suggesting that the liming practice is still insufficient and/or inadequate. Build-up the soil fertility to obtain high yields in the Cerrado region depends on the continuous application of liming and fertilizers (Benites et al. 2010). Cerrado soils, before the agricultural use (Lopes & Cox 1977), presented Ca^{2+} contents ranging from 0.04 to 6.8 $cmol_c$ dm^{-3} (median = 0.25 $cmol_c$ dm^{-3}). Mg^{2+} contents ranged from 0 to 2.2 $cmol_c$ dm^{-3} (median = 0.25 $cmol_c$ dm^{-3}) (Lopes & Guilherme 2016). Comparing the results of exchangeable Ca^{2+} and Mg^{2+} contents obtained herein, the median for Ca^{2+} was elevated to 2.1 $cmol_c$ dm^{-3}, and the median for Mg^{2+} increased from 0.25 to 0.6 $cmol_c$ dm^{-3} (Table I), indicating an increase of these nutrients in Cerrado soils through the years.

Regarding available K^+ content, 24% of samples presented very low and low levels (< 40 mg dm^{-3}); 28 % medium contents; and 48 % contents above the critical level (Figure 2p). The available K^+ contents in Cerrado agricultural soils from TMAP region were relatively high compared to native Cerrado soils (Lopes & Cox 1977). Available K^+ contents ranged from 8 to 942 mg kg^{-1} (mean = 99 mg dm^{-1} and median = 69 mg kg^{-1}) (Table I), while in native Cerrado soils available K^+ content ranging from 8 to 283 mg kg^{-1} (median = 31 mg kg^{-1}) (Lopes & Guilherme 2016). Adequate available K^+ contents are very important to obtain high yields and quality of products, however, excessive K^+ in the soil can compromise the equilibrium and, consequently, the availability of Ca^{2+} and Mg^{2+} for crops (Oliveira et al. 2001, Barros et al. 2010). Availability of K^+ in tropical soils is strongly dependent on the continuous fertilization through mineral fertilizers, adequate splitting, mainly in coarser texture soils and with low organic matter content, and continuous increasing of soil organic matter favoring K retention (Lana et al. 2004, Benites et al. 2010, Rosolem et al. 2012). Only coffee areas presented available K^+ contents higher than the critical limit (Figure 5m).

Most of samples (92%) had Ca/Mg ratio below than 6:1, ranging from 1.00 to 5.92 (Table II). Only 27% of samples had adequate Ca/K ratio (between 5:1 to 10:1), and 38% adequate Mg/K ratio (between 1:1 to 2:1). Most of samples (55%) had Mg^{2+} content on CEC considered adequate (between 4-12%). However, all samples did not reach satisfactory Ca^{2+} concentration on CEC2 (at least 65%). Regarding K^+, 56% of samples have adequate saturation on CEC2, ranging from to 2.00 to 4.98%. The monitoring of the relationships among these cationic macronutrients is crucial due to antagonistic interaction during uptake process. For example, the needed increasing in the Ca^{2+} concentration must be accomplished by liming and/or gypsum application, and an adequate Mg and K fertilization. The land use also impacted Ca, Mg, and K ratios, mainly Ca saturation on CEC2 (Figures 6a, b, c, d, e and f). In addition to absolute concentration of Ca^{2+}, Mg^{2+}, and K^{+}, adequate ratios among these nutrients also influence plant growth and productivity (Oliveira et al. 2001).

Sulfur

Sulfur interpretation was performed based on P-rem (Figures 2m, 2n and 2o). Samples that presented P-rem from 0 to 4 mg L^{-1} (more reactive and very clayey soils), the S availability was very good (100% of samples), with values superior to 5.4 mg dm^{-3} in all samples (Figure 2m). For samples with higher P-rem values, the S availability decreased. For P-rem class from 4 to 10 mg L^{-1}, 83 % of samples presented very good contents; 10 % good; and only 2% medium contents (Figure 2n). For P-rem class from 10 to 19 mg L^{-}, the percentage of samples with very good content decreased to 39%; 30% of samples presented good contents; 21% medium contents; and 10 % had low contents (Figure 2o). Sulfur in agricultural systems is related to the application of gypsum (Lopes & Guilherme 2016) and to other fertilizers that contain sulfur in their formulation such as ammonium sulfate (24 % of S), simple superphosphate (12 % of S), and magnesium sulfate (13 % of S) (Broch et al. 2011) that are applied to supply other nutrients. Gypsum ($CaSO_4$) application in agricultural soils, mainly in tropical conditions, is an efficient way to reduce Al^{3+} availability in deeper layers. This is possible due to elevated mobility of SO_4^{2-} down soil profile and by formation of $AlSO_4^{+}$ precipitated (Fageria & Baligar 2008). Also, the movement of SO_4^{2-} through the soil profile can transport cations like Ca, Mg, and K (Crusciol et al. 2014, Pauletti et al. 2014). This process can enrich subsurface layers (Caires et al. 2004, Neis et al. 2010) favoring the development of roots (Caires et al. 2001, Crusciol et al. 2014, Pauletti et al. 2014). However, an excessive leaching can cause a depletion of Ca^{2+}, Mg^{2+}, and K^{+} in the upper soil layers. The suitable gypsum application has increased yields of different crops growing in the Cerrado region (Caires et al. 2001, Crusciol et al. 2014, Pauletti et al. 2014). Herein, satisfactory contents of S were observed only in coffee areas (Figure 5l).

Micronutrients

The concentrations of Fe, Mn, Zn, and Cu (Figures 4a, 4b, 4c and 4d, respectively) were higher than the critical contents in 80%, 82%, 70%, and 72% of the samples, respectively. Most samples showed very high concentrations, especially Mn and Zn (Figures 4b and 4c). This diagnostic is especially important for Zn, since it has been increasing considered in biofortification strategies of crops (Cakmak 2008, Cakmak et al. 2010, Oliveira et al. 2018). This current condition differs significantly from native Cerrado soils which are characterized by a generalized micronutrients deficiency (Marques et al. 2004, Pegoraro et al. 2006, Lopes & Guilherme 2016). The effects of micronutrient deficiency on reduction of crops yield are well known (Carmo et al. 2012, Kurtz & Ernani 2010).

An unsatisfactory result was observed only for B. Almost all samples (97%) showed concentrations lower than the critical level (<0.6 mg dm^{-3}) (Figure 4e). B is an important plant micronutrient participating in many physiological processes. Due to its low mobility in plants, B fertilization should be preferentially performed via soil (Bologna & Vitti 2006, Furtini Neto et al. 2001, Mattiello et al. 2009). Also, even

Table II. Ca, Mg, and K ratios in soil samples from Triângulo Mineiro and Alto Paranaíba region, Cerrado biome, Brazil.

Ratio	Min.	Max.	Mean	Median	s.d	AI	% of AI	Skewness	Kolmogorov-Smirnov
Ca/K	0.7	70.0	13.4	9.9	11.5	5:1 to 10:1	27.0	2.3	0.14 n.s
Ca/Mg	0.5	14.3	3.9	3.7	2.0	6:1 to 10:1	8.0	1.7	0.08 n.s
Mg/K	0.3	20.7	3.9	2.6	3.4	1:1 to 2:1	38.0	1.9	0.16 n.s
Ca/CEC2	0.6	73.0	34.8	36.4	15.5	65 to 85%	0.0	-0.2	0.06 n.s
Mg/CEC2	1.2	30.1	10.2	9.2	5.3	4 to 12%	55.0	0.9	0.08 n.s
K/CEC2	0.4	23.3	3.9	3.1	3.1	2 to 5%	56.0	2.7	0.17 n.s

AI: best adequate interval for plant growth per Bear & Toth (1948), Adams & Henderson (1962), and Liebhardt (1981); % of AI means the percentage of samples with adequate ratio; s.d.: standard deviation; n.s: non-significant.

with frequent and adequate applications as H_3BO_3 its residual effect in soils is low (Resende et al. 2016). H_3BO_3 is the predominant form of B in soils and it can be easily leached, mainly in sandy soils and low soil organic matter content (Gondim 2009, Bologna 2003). For some crops (e.g., coffee), emergency applications of B via foliar fertilization may be needed. Coffee plants are one of the most sensitive and responsive species to B. Its deficiency causes reduction in the root and shoot development, flower abortion, fruit malformation, deformities in vascular elements, and, consequently, yield reduction (Rosolem & Leite 2007, Gontijo et al. 2008). Adequate B concentrations were observed only in coffee areas in the TMAP mesoregion (Figure 5t) reinforcing the importance given by farmers to this micronutrient (Poltronieri et al. 2016).

The available Fe contents were lower in all TMAP land uses compared to native Cerrado vegetation (Figure 5s). This may be attributed to the increase in soil pH due to liming (Raij 2011) favoring its precipitation and reducing the availability. For Cu, coffee and horticulture areas showed the highest values (Figure 5q). In horticultural areas, there was also a greater variation in soil Cu content, which can be attributed to the use of fungicides for preventive disease control, which contain Cu and Zn in their composition (Mackie et al. 2012). It is known that frequent applications may increase the concentrations of Cu and Zn in soils (Nagajyoti et al. 2010). The same result was observed for Zn (Figure 5p), with higher levels found in coffee and horticultural areas. No significant differences between land uses were observed for Mn (Figure 5r).

Comparing the results found herein with those reported by Lopes & Guilherme (2016) for native Cerrado soils, a significant increase in the concentration of micronutrients occurred. As reported by Lopes & Guilherme (2016), native Cerrado soils had Fe contents ranging from 3.7 to 74 mg dm^{-3} (median = 32 mg dm^{-3}). Cu and Zn contents ranged from 0 to 9.7 mg dm^{-3} (median = 0.6 mg dm^{-3}); Mn from 0.6 to 92 mg dm^{-3} (median = 7.6 mg dm^{-3}) (Lopes & Guilherme 2016). All natural concentrations for Cu, Zn, and Mn are below the critical levels for crop growing (Lopes & Guilherme 2016). Currently, these micronutrients are not limiting factors for agricultural production in the studied area (Figures 4 and 5). Most concentrations of Cu, Zn, and Mn are higher than the critical values (Figure 4). Considering the adequate concentrations of micronutrients (Fe, Cu, Mn, and Zn) in the TMAP

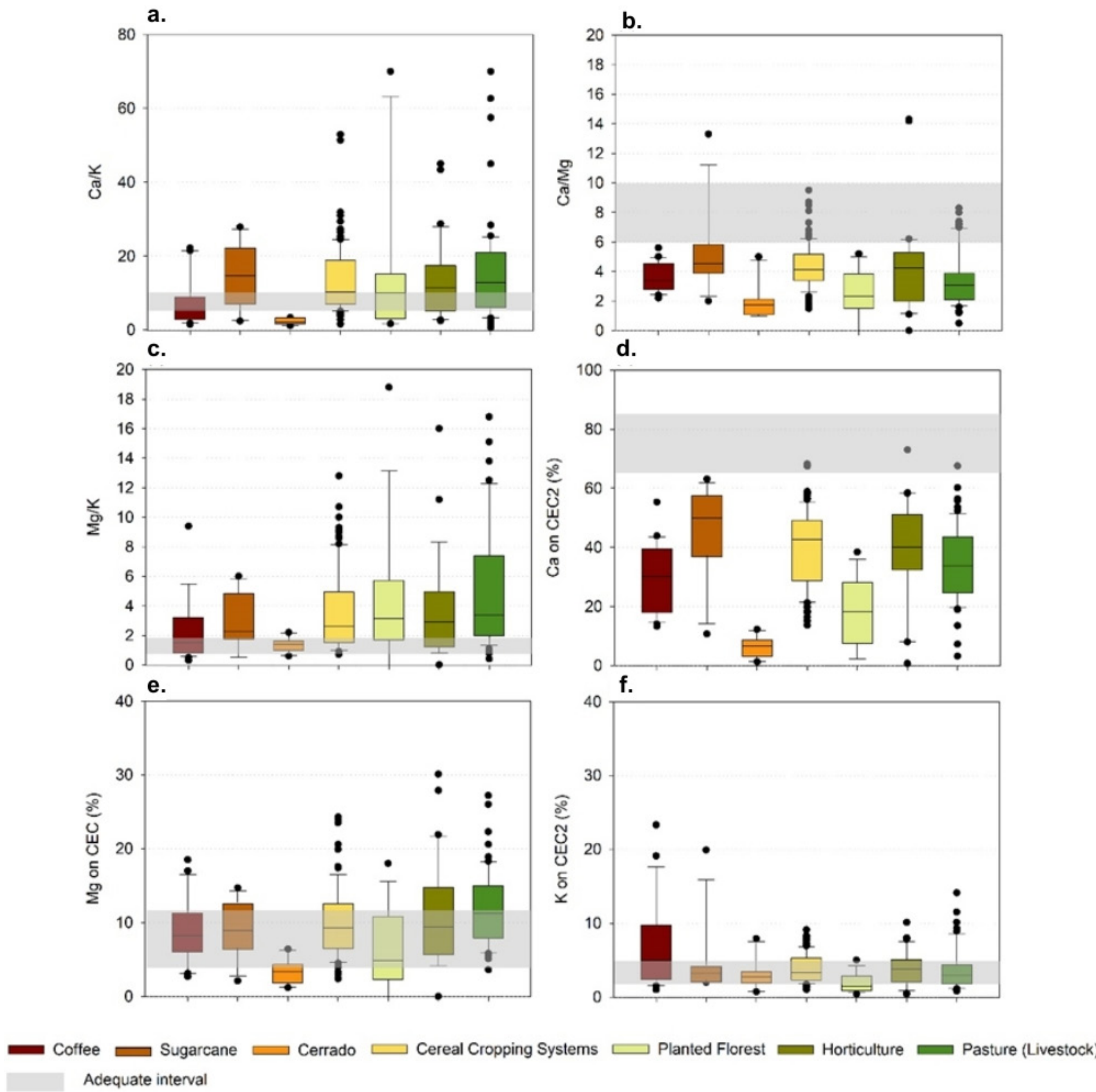

Figure 6. Effect of land use in the TMAP region on Ca, Mg, and K ratios. Best adequate interval for plant growth per Bear & Toth (1948), Adams & Henderson (1962), and Liebhardt (1981).

mesoregion biofortification strategies of crops (e.g., with Zn) can be facilitated (Cakmak 2008, Cakmak et al. 2010, Oliveira et al. 2018).

In this work an important agricultural mesoregion in the Cerrado biome was studied to report a diagnose of soil fertility conditions. Compared to native Cerrado soils, the soil pH and CEC increased being attributed to continuous adoption of liming. Consequently, exchangeable Al^{3+} and its saturation on CEC were drastically reduced. However, mainly planted forests and some cereal crops are still growing in poor conditions. The increasing in the soil organic matter content is still a challenge. All studied land uses in the TMAP mesoregion did not significantly differ the SOM from native Cerrado areas. Thus, continuous adoption of best management practices (e.g., no-tillage) and supplementary organic fertilization must be encouraged. As result of continuous mineral fertilization through the years, available K^+, exchangeable Ca^{2+} and Mg^{2+}, and S significantly increased compared to native condition. However, satisfactory contents (above the critical content) have not been yet achieved, especially for Mg. This result suggests more attention on the use of Mg-enriched limestones instead the continuous application of calcitic limestones. The micronutrients (Fe, Cu, Mn, and Zn) in the TMAP region were considered satisfactory. This finding is special important for successful implementation of biofortification strategies in the TMAP region (e.g., with Zn). Only B was considered complete unsatisfactory. Except for coffee areas, all land uses in the TMAP mesoregion presented B concentration significantly below the critical content.

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REFERENCES

ABDALA DB, GHOSH AK, DA SILVA IR, DE NOVAIS RF & VENEGAS VHA. 2012. Phosphorus saturation of a tropical soil and related P leaching caused by poultry litter addition. Agric Ecosyst Environ 162: 15-23.

ADAMS F & HENDERSON JB. 1962. Magnesium availability as affected by deficient and adequate levels of potassium and lime. Soil Sci Soc Am Proc 26: 65-68.

ALVAREZ VVH, NOVAIS RF, BARROS NF, CANTARUTTI RB & LOPES AS. 1999. Interpretação dos resultados das análises de solos. In: Ribeiro AC, Guimaraes PTG & Alvarez VVH (Eds.), Recomendação para o uso de corretivos e fertilizantes em Minas Gerais: 5º Aproximação. Viçosa: Comissão de Fertilidade do Solo do Estado de Minas Gerais, p. 25-32.

ALVAREZ VVH, NOVAIS RF, DIAS LE & OLIVEIRA JÁ. 2000. Boletim Informativo da Sociedade Brasileira de Ciência do Solo, v. 25, p. 27-32.

ALVAREZ-PUEBLA RA, OULET PJG & ARRIDO JJ. 2005. Characterization of the porous structure of different humic fractions. Colloids and Surfaces A: Physicochemical and Engineering Aspects, Amsterdam, v. 256, p. 129-135. DOI: 10.1016/j. colsurfa.2004.12.062.

BARROS AC, FOLEGATTI MV, SOUZA CF & SANTORO BL. 2010. Distribuição da solução no solo aplicado por gotejamento enterrado e superficial. Irriga 15: 361-372.

BARROW NJ & DEBNATH A. 2014. Effect of phosphate status on the sorption and desorption properties of some soils of northern India. Plant Soil 378: 383-395.

BAYER C & MIELNICZUK J. 2008. Dinâmica e função da matéria orgânica. In: Santos GA, Silva LS, Canellas LP & Camargo FAO (Eds.), Fundamentos da matéria orgânica do solo: ecossistemas tropicais e subtropicais, 2nd ed., Porto Alegre: Metrópole, p. 7-18.

BEAR FE & TOTH ST. 1948. Influence of calcium on other soil cations. Soil Sci 63: 69-75.

BENITES VM, CARVALHO MCS, RESENDE AV, POLIDORO JC, BERNARDI ACC & OLIVEIRA FA. 2010. Potássio, cálcio e magnésio. In: Prochnow LI, Casarin V & Stipp SR (Eds.), Boas práticas para uso eficiente de fertilizantes: Nutrientes. Piracicaba: IPNI Brasil 2: 133-204.

BEZERRA RPM, LOSS A, PEREIRA MG & PERIN A. 2015. Frações de fósforo e correlação com atributos edáficos sob sistemas de plantio direto e integração lavoura-pecuária no Cerrado Goiano. Semina Ciênc Agrár 36: 1287-1306.

BOLOGNA IR. 2003. Adubação Boratada em Pomar de Laranja Pêra Rio Afetado pela Clorose Variegada dos Citros. Dissertação (Mestrado) - Escola Superior de

Agricultura “Luiz de Queiroz” – Esalq/USP, Piracicaba. (Unpublished).

BOLOGNA IR & VITTI GC. 2006. Produção e qualidade de frutos de laranjeira ‘Pêra’ em função de fontes e doses de boro. Rev Bras Frutic 28: 328-330.

BRADY NC & WEIL RR. 2013. Elementos da natureza e propriedades dos solos, 3rd ed., Porto Alegre: Bookman, 704 p.

BROCH DL, PAVINATO PS, POSSENTTI JC, MARTIN TN & DEL QUIQUI EM. 2011. Produtividade da soja no cerrado influenciada pelas fontes de enxofre. Rev Ciênc Agron 42: 791-796.

BRONICK CJ & LAL R. 2005. Soil structure and management: a review. Geoderma 124: 3-22.

BUSTAMANTE MMC, CORBEELS M, SCOPEL E & ROSCOE R. 2006. Soil carbon and sequestration potential in the Cerrado Region of Brazil. In: Lal R, Cerri CC, Bernoux M, Etchevers J & Cerri CEP (Eds.), Carbon sequestration in soils of Latin America, New York, Haworth, p. 285-304. DOI: 10.1201/9781482298031-23.

CAIRES EF, FELDHAUS IC & BLUM J. 2001. Crescimento radicular e nutrição da cevada em função da calagem e aplicação de gesso. Bragantia 60: 213-223.

CAIRES EF, KUSMAN MT, BARTH G, GARBUIO FJ & PADILHA JM. 2004. Alterações químicas do solo e resposta do milho à calagem e aplicação de gesso. Rev Bras Ciênc Solo 28: 125-136.

CAKMAK I. 2008. Enrichment of cereal grains with zinc: agronomic or genetic biofortification? Plant Soil 302: 1-17.

CAKMAK I, PFEIFFER WH & MCCLAFFERTY B. 2010. Biofortification of durum wheat with zinc and iron. Cereal Chem J 87: 10-20.

CANELLAS LP, SANTOS GA & AMARAL-SOBRINHO NMB. 1999. Reações da matéria orgânica. In: Santos GA & Camargo FAO (Eds.), Fundamentos da matéria orgânica do solo: ecossistemas tropicais e subtropicais, 2nd ed., Porto Alegre: Metrópole, p. 69-90.

CANTARUTTI RB, BARROS NF, MARTINEZ HEP & NOVAIS RF. 2007. Avaliação da Fertilidade do Solo e Recomendação de Fertilizantes. In: Novais RF, Alvarez VVH, Barros NF, Fontes RLF, Cantarutti RB & Neves JCL (Eds.), Fertilidade do Solo. Viçosa: Sociedade Brasileira de Ciência do Solo, p. 769-872.

CARMO DLD, NANNETTI DC, LACERDA TM, NANNETTI NA & SANTO DJDE. 2012. Micronutrientes em solo e folha de cafeeiro sob sistema agroflorestal no sul de Minas Gerais. Coffee Sci 7: 76-83.

CARVALHO JLN, AVANZI JC, SILVA MLN, MELLO CR & CERRI CEP. 2010. Potencial de sequestro de carbono em diferentes biomas do Brasil. Rev Bras Ciênc Solo 34: 277-289.

CHELOTTI MC & ROSOLEN V. 2014. Dinâmica da agropecuária e uso da terra na mesorregião do Triângulo Mineiro/Alto Paranaíba (MG). Campo – Territ: 1-19.

COSTA NR, ANDREOTTI M, BUZETTI S, LOPES KSM, SANTOS FGD & PARIZ CM. 2014. Acúmulo de macronutrientes e decomposição da palhada de braquiárias em razão da adubação nitrogenada durante e após o consórcio com a cultura do milho. Rev Bras Ciênc Solo 38: 1223-1233.

CRUSCIOL CAC, FOLTRAN R, ROSSATO OB, MCCRAY JM & ROSSETTO R. 2014. Efeito da aplicação superficial de silicato de cálcio-magnésio e de gesso na fertilidade do solo e produtividade da cana-de-açúcar. Rev Bras Ciênc Solo 38: 1843-1854.

CRUSCIOL CA, SORATTO RP, BORGHI E & MATHEUS GP. 2010. Benefits of integrating crops and tropical pastures as systems of production. Better Crops 94: 14-16.

FAGERIA NK & BALIGAR VC. 2008. Ameliorating soil acidity of tropical Oxisols by liming for sustainable crop production. Adv Agron 99: 345-399.

FEAM - FUNDAÇÃO ESTADUAL DO MEIO AMBIENTE. 2010. Mapa de solos de Minas Gerais: legenda expandida. Available in: http://www.feam.br/-qualidade-do-solo-e-areas-contaminadas/mapa-de-solos. Access in: May 14 2024.

FURTINI NETO AE, VALE FR, RESENDE AV, GUILHERME LRG & GUEDES GAA. 2001. Fertilidade do solo. Lavras: UFLA/FAEPE, 252 p.

GEE GW & BAUDER JW. 1986. Particle-size analysis. In: Klute A (Ed.), Methods of soil analysis: part 1, 2nd ed., Madison: ASA/SSSA, p. 383-411. DOI: 10.2136/sssabookser5.1.2ed.c15.

GHOSH AK, BARBOSA J & SILVA IR. 2011. An environmental threshold of soil test P and degree of P saturation of Brazilian Oxisols. Clean - Soil Air Water 39: 421-427.

GMACH MR, DIAS BO, SILVA CA, NÓBREGA JCA, LUSTOSA-FILHO JF & SIQUEIRA NETO M. 2018. Soil organic matter dynamics and land-use change on Oxisols in the Cerrado, Brazil. Geoderma Reg 14: e00178.

GONDIM ARO. 2009. Absorção e mobilidade do boro em plantas de tomate e de beterraba. 2009. 76 f. Tese (Doutorado em Agronomia) - Faculdade de Ciências Agrárias e Veterinárias, Universidade Estadual Paulista “Júlio de Mesquita Filho” – UNESP, Jaboticabal.

GONTIJO RAN, GUIMARÃES RJ & CARVALHO JG. 2008. Crescimento e teor foliar de nutrientes em cafeeiro decorrente da omissão isolada e simultânea de Ca, B, Cu e Zn. Coffee Sci 3: 124-132.

GROPPO JD ET AL. 2015. Changes in soil carbon, nitrogen, and phosphorus due to land-use changes in Brazil. Biogeosciences 12: 4765-4780.

GUARESCHI RF, PEREIRA MG & PERIN A. 2012. Deposição de resíduos vegetais, matéria orgânica leve, estoques de carbono e nitrogênio e fósforo remanescente sob diferentes sistemas de manejo no cerrado goiano. Rev Bras Ciênc Solo 36: 909-920.

IBGE - INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA. 2018. Sistema IBGE de Recuperação Automática – SIDRA. Available in: www.sidra.ibge.gov.br. Access in: Dec 18 2022.

IBGE - INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA. 2024. Downloads Geociências. Available in: https://geoftp.ibge.gov.br/informacoes_ambientais/pedologia/vetores/brasil_5000_mil/. Access in: May 14 2024.

KURTZ C & ERNANI PR. 2010. Produtividade de cebola influenciada pela aplicação de micronutrientes. Rev Bras Ciênc Solo 34: 133-142.

LANA RMQ, ZANÃO JÚNIOR LA, KORNDORFER GH & MACIEL JUNIOR VA. 2004. Parcelamento da adubação potássica na cana-planta. Rev STAB: Açúcar Álcool Subprod 23: 28-31.

LANDAU EC, MOURA L, GUIMARAES DP & HIRSCH A. 2018. Dinâmica Espaço-Temporal da Produção de Milho, Soja e Café no Estado de Minas Gerais entre 1990 e 2016. Sete Lagoas: Embrapa Milho e Sorgo, 79 p.

LIEBHARDT W. 1981. The basic cation saturation ratio concept and lime and potassium recommendations on Delaware's coastal plain soils. J Soil Sci Soc Am 45: 4-9.

LOPES AS. 1975. A survey of the fertility status of surface soils under "Cerrado" vegetation in Brazil (1975). Dissertação (Mestrado) – Departamento de Ciência do Solo, Universidade da Carolina do Norte – EUA, Raleigh. (Unpublished).

LOPES AS & COX FR. 1977. A survey of the fertility status of soils under Cerrado vegetation in Brazil. Soil Sci Soc Am J 41: 742-747.

LOPES AS & GUILHERME LRG. 2016. A career perspective on soil management in the Cerrado Region of Brazil. Adv Agron 137: 1-72.

LOPES AS, GUILHERME LRG & RAMOS SJ. 2012. The saga of the agricultural development of the brazilian Cerrado. Electronic International Fertilizer Correspondent 32: 29-57.

LOSS A, PEREIRA MG, GIÁCOMO SG, PERIN A & ANJOS LHCD. 2011. Agregação, carbono e nitrogênio em agregados do solo sob plantio direto com integração lavoura-pecuária. Pesqui Agropec Bras 46: 1269-1276.

MACKIE KA, MUELLER T & KANDELER E. 2012. Remediation of copper in vineyards: a mini review. Environ Pollut 167: 16-26.

MARQUES JJ, SCHULZE DG, CURI N & MERTZMAN SA. 2004. Major element geochemistry and geomorphic relationships in Brazilian Cerrado soils. Geoderma 119: 179-195.

MATTIELLO EM, RUIZ HA, SILVA IRD, BARROS NFD, NEVES JCL & BEHLING M. 2009. Transporte de boro no solo e sua absorção por eucalipto. Rev Bras Ciênc Solo 33: 1281-1290.

MORAES MT, DEBIASI H, CARLESSO R, FRANCHINI JC, SILVA VR & LUZ FB. 2016. Soil physical quality on tillage and cropping systems after two decades in the subtropical region of Brazil. Soil Tillage Res 155: 351-362.

NAGAJYOTI PC, LEE KD & SREEKANTH SVM. 2010. Heavy metals, occurrence and toxicity for plants: a review. Environ Pollut 8: 199-216.

NEIS L, PAULINO HB, SOUZA EDD, REIS EFD & PINTO FA. 2010. Gesso agrícola e rendimento de grãos de soja na região do sudoeste de Goiás. Rev Bras Ciênc Solo 34: 409-416.

NELSON DW & SOMMERS LE. 1996. Total carbon, organic carbon and organic matter. In: Sparks DL, Paga AL, Helmke PA, Loeppert RH, Soltanpour PN, Tabatabai MA, Johnston CT & Summer ME (Eds.), Methods of soil analysis: Chemical methods. Part 3. Soil Science Society of America, p. 961-1010. DOI: 10.2136/sssabookser5.3.c34.

OLIVEIRA ES, REATTO A & ROIG HL. 2015. Estoques de carbono do solo segundo os componentes da paisagem. CC&T 32: 71-93.

OLIVEIRA FA, CARMELLO QAC & MASCARENHAS HAA. 2001. Disponibilidade de potássio e suas relações com cálcio e magnésio em soja cultivada em casa de vegetação. Sci Agric 58: 329-335.

OLIVEIRA VC, FAQUIN V, GUIMARÃES KC, ANDRADE FR, PEREIRA J & GUILHERME LRG. 2018. Agronomic biofortification of carrot with selenium. Ciênc Agrotec 42: 138-147.

PACHECO LP, PIRES FR, MONTEIRO FP, PROCÓPIO SDO, ASSIS RLD, CARMO MLD & PETTER FA. 2008. Desempenho de plantas de cobertura em sobressemeadura na cultura da soja. Pesqui Agropec Bras 43: 815-823.

PAULETTI V, PIERRI LD, RANZAN T, BARTH G & MOTTA ACV. 2014. Efeitos em longo prazo da aplicação de gesso e calcário no sistema de plantio direto. Rev Bras Ciênc Solo 38: 495-505.

PEGORARO RF, SILVA IR, NOVAIS RF, MENDONÇA EDS, ALVAREZ VVH, NUNES FN & GEBRIM FO. 2006. Fluxo difusivo de micronutrientes catiônicos afetado pelo tipo, dose e época de incorporação de adubos verdes ao solo. Rev Bras Ciênc Solo 30: 997-1006.

POLTRONIERI Y, MARTINEZ HEP, CLEMENTE JM & FERREIRA AO. 2016. Fornecimento de boro, cobre e zinco ao cafeeiro via inserção de comprimidos no ramo ortotrópico. Coffee Sci 11: 521-529.

POMPEU J, ASSIS TO, OMMETTO JP. 2024. Landscape changes in the Cerrado: Challenges of land clearing, fragmentation and land tenure for biological conservation. Sci Total Environ 906: 167581.

POZZA LE & FIELD DJ. 2020. The science of soil security and food security. Soil Security 1: 100002.

R CORE TEAM. 2022. A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. URL. https://www.R-project.org/.

RAIJ BV, ANDRADE JC, CANTARELLA H & QUAGGIO JA. 2001. Análise química para avaliação da fertilidade de solos tropicais. Instituto Agronômico de Campinas, 285 p.

RAIJ BV. 2011. Fertilidade do solo e manejo de nutrientes. International Plant Nutrition Institute, 420 p.

RAIJ BV, CANTARELLA H, QUAGGIO JA, PROCHNOW LI, VITTI GC & PEREIRA HS. 1994. SOIL TESTING AND PLANT ANALYSIS IN BRAZIL. COMMUN SOIL SCI PLANT ANAL 5:739-751.

RESENDE AV, FONTOURA SMV, BORGHI E, SANTOS FC, KAPPES C, MOREIRA SG, OLIVEIRA JR A & BORIN ALDC. 2016. Solos de fertilidade construída: características, funcionalidades e manejo. Informações Agronômicas 156: 1-19.

RODRIGUES M, PAVINATO PS, WITHERS PJA, TELES APB & HERRERA WFB. 2016. Legacy phosphorus and no tillage agriculture in tropical oxisols of the Brazilian savanna. Sci Total Environ 542: 1050-1061.

ROSOLEM CA & LEITE VM. 2007. Coffee leaf and stem anatomy under boron deficiency. Rev Bras Ciênc Solo 31: 477-483.

ROSOLEM CA, VICENTINI JPTMM & STEINER F. 2012. Suprimento de potássio em função da adubação potássica residual em um Latossolo Vermelho do Cerrado. Rev Bras Ciênc Solo 36: 1507-1515.

ROY ED, WILLIG E, RICHARDS PD, MARTINELLI LA, VAZQUEZ FF, PEGORINI L, SPERA SA & PORDER S. 2017. Soil phosphorus sorption capacity after three decades of intensive fertilization in Mato Grosso, Brazil. Agric Ecosyst Environ 249: 206-214.

SÁ JCM, SEGUY L, SÁ MFM, FERREIRA AO, BRIEDIS C, SANTOS JB & CANALLI LBS. 2010. Gestão da matéria orgânica e da fertilidade do solo visando sistemas sustentáveis de produção. Boas práticas para uso eficiente de fertilizantes. Piracicaba: International Plant Nutrition Institute, p. 5-46.

SADE H, MERIGA B, SURAPU V, GADI J, SUNITA MS, SURAVAJHALA P & KISHOR PBK. 2016. Toxicity and tolerance of aluminum in plants: tailoring plants to suit to acid soils. Biometals 29: 187-210.

SALTON JC, MIELNICZUK J, BAYER C, FABRÍCIO AC, MACEDO MCM & BROCH DL. 2011. Teor e dinâmica do carbono no solo em sistemas de integração lavoura-pecuária. Pesqui Agropecu Bras 46: 1349-1356.

SANO EE, ROSA R, BRITO JLS & FERREIRA LG. 2010. Land cover mapping of the tropical savanna region in Brazil. Environ Monit Assess 166: 113-124.

SANTOS HG, JACOMINE PKT, ANJOS LHC, OLIVEIRA VA, LUMBRERAS JF, COELHO MR, ALMEIDA JA, ARAUJO FILHO JC, OLIVEIRA JB & CUNHA TJF. 2018. Sistema brasileiro de classificação de solos, 5th ed., Brasília, DF: Embrapa.

SATO JH, FIGUEIREDO CCD, LEÃO TP, RAMOS ML & KATO E. 2012. Matéria orgânica e infiltração da água em solo sob consórcio milho e forrageiras. Rev Bras Eng Agríc Ambient 16: 189-193.

SILVA PRFD, ARGENTA G, SANGOI L, STRIEDER ML & SILVA AAD. 2006. Estratégias de manejo de coberturas de solo no inverno para cultivo do milho em sucessão no sistema semeadura direta. Cienc Rural 36: 1011-1020.

IDE-SISEMA - SISTEMA ESTADUAL DE MEIO AMBIENTE E RECURSOS HÍDRICOS. 2024. Infraestrura de Dados Espaciais. Available in: https://idesisema.meioambiente.mg.gov.br/webgis. Access in: May 14 2024.

SOIL SURVEY STAFF. 2014. Keys to soil taxonomy, 12th ed., USDA-NRCS, Washington, DC.

SOLTANGHEISI A, RODRIGUES M, COELHO MJA, GASPERINI AM, SARTOR LR & PAVINATO PS. 2018. Changes in soil phosphorus lability promoted by phosphate sources and cover crops. Soil Tillage Res 179: 20-28.

SOUZA JL, GUIMARÃES GP & FAVARATO LF. 2015. Desenvolvimento de hortaliças e atributos do solo com adubação verde e compostos orgânicos sob níveis de N. Hortic Bras 33: 19-26.

SOUZA RFD, FAQUIN V, TORRES PRF & BALIZA DP. 2006. Calagem e adubação orgânica: influência na adsorção de fósforo em solos. Rev Bras Ciênc Solo 30: 975-983.

SYSTAT SOFTWARE INC. 2006. Sigmaplot for Windows, version 10. Available in: https://systatsoftware.com/download-systat-software/. Access May 24 2024.

TEIXEIRA PC, DONAGEMMA GK, FONTANA A & TEIXEIRA WG. 2017. Manual de métodos de análise de solo, 3rd ed., Brasília, DF: Embrapa: 574 p.

VITTI GC & SUZUKI JA. 1978. A determinação do enxofre: sulfato pelo método turbidimétrico. Jaboticabal: Universidade Estadual de São Paulo, 13 p.

VITTI GC & TREVISAN. 2000. Manejo de macro e micronutrientes para alta produtividade da soja. Piracicaba: Informações Agronômicas 90: 1-16.

YAMADA T. 2005. The Cerrado of Brazil: a success story of production on acid soils. Soil Sci Plant Nutr 51: 617-620.

ZOTARELLI L, ZATORRE NP, BODDEY RM, URQUIAGA S, JANTALIA CP, FRANCHINI JC & ALVES BJ. 2012. Influence of no-tillage and frequency of a green manure legume in crop rotations for balancing N outputs and preserving soil organic C stocks. Field Crop Res 132: 185-195.

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TATIANE M. DE LIMA[1]
https://orcid.org/0000-0001-5536-6040

MARCELA V. DA COSTA[2]
https://orcid.org/0000-0001-8016-5291

REGINA MARIA Q. LANA[1]
https://orcid.org/0000-0002-7034-674X

ATHOS GABRIEL G. NASCIMENTO[1]
https://orcid.org/0000-0002-8717-7890

DIOGO CÉSAR P. DIAS[1]
https://orcid.org/0000-0002-5075-5503

BRUNO T. RIBEIRO[2]
https://orcid.org/0000-0003-3108-1125

[1]Universidade Federal de Uberlândia, Instituto de Ciências Agrárias, Rodovia LMG, 746, Km 01, Bairro Araras, 38500-000 Monte Carmelo, MG, Brazil

[2]Universidade Federal de Lavras, Departamento de Ciência do Solo, Trevo Rotatório Professor Edmir Sá Santos, s/n, Caixa Postal 3037, 37203-202 Lavras, MG, Brazil

Correspondence to: **Bruno Teixeira Ribeiro**
E-mail: brunoribeiro@ufla.br

Author contributions

TATIANE M. DE LIMA: conceptualization, field work, laboratory analyses, statistical analysis and writing. MARCELA V. DA COSTA: statistical analysis, graphs and review. REGINA MARIA Q. LANA: conceptualization, supervision and review. ATHOS GABRIEL G. NASCIMENTO: field work and laboratory analyses. DIOGO CÉSAR P. DIAS: field work and laboratory analyses. BRUNO T. RIBEIRO: conceptualization, writing and English review.