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Distribution of available nitrogen forms in soil under *Quilombola* management systems in Brazilian Cerrado phytophysiognomies

Antonio Marcos Miranda Silva[1*], Maria Lucrécia Gerosa Ramos[2], Robervone Severina de Melo Pereira do Nascimento[3], Henrique Petry Feiler[1], Stefany Braz Silva[2], Elke Jurandy Bran Nogueira Cardoso[1]

[1]Universidade de São Paulo/ESALQ – Depto. de Ciência do Solo, Av. Pádua Dias, 11 – 13418-900 – Piracicaba, SP – Brasil.
[2]Universidade de Brasília/Faculdade de Agronomia e Medicina Veterinária – Campus Universitário Darcy Ribeiro, Bloco B, Asa Norte – 70910-970 – Brasília, DF – Brasil.
[3]Instituto Nacional de Colonização e Reforma Agrária, SBN QD 01 Bloco D, Edifício Palácio do Desenvolvimento – 70057-900 – Brasília, DF – Brasil.
*Corresponding author <antoniomarcos@usp.br>

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ABSTRACT: Management of *Quilombola* systems are primitive agricultural systems based on the ancestral knowledge of Afro-Brazilian enslaved people. Here, the aim was to understand the impact of these primitive farming methods on the distribution of available nitrogen (N) forms in the soil profile of two Brazilian Cerrado phytophysiognomies. The soil was sampled in *Cerradão* (high Cerrado) and Cerrado *Stricto sensu* (low Cerrado) at six soil depths (0-10, 10-20, 20-30, 30-40, 40-50, and 50-60 cm). The following management systems were considered: pasture (PP1 and PP2), maize cultivation (M1 and M2), citrus-cassava intercropping (T1), and citrus monoculture (T2). In addition, the soil was sampled in the native area of *Cerradão* (NC1) and Cerrado *Stricto sensu* (NC2). Three N forms were determined: i) available nitrogen (Av-N), ii) ammonium (NH_4^+-N) and iii) nitrate (NO_3^--N) contents. The Av-N content decreased with increasing soil depth only in NC1 and NC2. The NO_3^--N content was similar at all soil depths for maize and pasture, while the content decreased at soil depth for NC1, NC2, and T1. NH_4^+-N was similar in M2 and PP2, but it increased in T2, ranging from 6.17 mg kg^{-1} to 17.54 mg kg^{-1}. Overall, the dynamics of available N forms varied according to the Cerrado phytophysiognomy and the management systems and NO_3^--N was the most constant N form in the soil profile. Therefore, although the management of *Quilombola* systems is less intensive, they negatively affect the dynamics and N availability, mainly where management is less conservative, that is, in maize and citrus monocultures.

Keywords: Brazilian Cerrado, tillage, soil profile assessment, soil nutrient distribution

Introduction

The Brazilian Cerrado is a Savannah-like region with a relatively dry climate covering 2 million km^2, representing 23 % of Brazil's total agricultural area, and is considered a hot spot for biodiversity (Ratter et al., 1997). Lately, the Cerrado has become the most important agricultural area for the Brazilian agribusiness, with significant technological development and high productivity for the national and international food markets (Colli et al., 2020). The Brazilian Cerrado presents different phytophysiognomies, usually comprised of weathered ancient soils. The weathering process has impoverished the soil chemically regarding nutrient contents and acidity, with high aluminum (Al) saturation. However, physically, Cerrado soils present high aggregation and stability (Dias et al., 2019; Silva et al., 2019). Woodland savannah (also referred to as typical savannah or Cerrado *Stricto sensu*) is the most prevalent phytophysiognomy in the Cerrado, presenting deeper soil covered by many tortuous trees, with thick barks and leathery leaves (Eiten, 1972). The second most prevalent phytophysiognomy is the *Cerradão* (high savannah), which shows a predominance of forest-like vegetation characterized by an almost closed canopy where the soil is not very deep nor very fertile (Ratter et al., 1997; Felfili and Fagg, 2007).

Many years before the agribusiness started to cultivate the Cerrado area, people of African ancestry, generally descendants of olden-time enslaved people, which succeeded in escaping from their masters by hiding in Cerrado areas far from cities or busy rural areas. There, they congregated and established small villages, which are called *Quilombos*. Their traditional agricultural systems, based on ancestral knowledge, may cause little interference with the original soil properties (Nascimento et al., 2017; Silva et al., 2019), at least when considering the traditional agriculture that uses many inputs. Furthermore, even in areas of traditional agriculture, such as *Quilombos* and indigenous communities, land-use change (LUC) may cause impacts on soil quality indicators, such as changes in carbon (C) and nitrogen (N) stocks (Kohler and Brondizio, 2017; Ramos et al., 2022). Thus, although many works show the success of conservative agricultural management systems in restoring soil health, little is known about this condition in communities where technical assistance is still neglected, as in *Quilombola* communities. Therefore, this research is considered groundbreaking to unravel the impact of *Quilombola* management systems on N distribution in the soil profile. It is important to highlight that N is one of the most limiting nutrients for crop production.

Materials and Methods

Site description and soil sampling

In this study, the distribution of available N forms in soil profiles was evaluated in different *Quilombola* management systems (pasture, maize, and citrus) in two Cerrado phytophysiognomies (*Cerradão* and *Stricto sensu*) (Figure 1). The sites are in *Quilombo Mesquita* in the municipality of Cidade Ocidental (Central portion of Goiás State) and Federal District of Brazil (16°04′41″ S, 47°52′05″ W, altitude 1014 m) as described in Silva et al. (2019) and Ramos et al. (2022). According to Köppen classification, the climate is Aw, with dry winters and rainy summers. The mean annual temperature is 21 °C and rainfall is 1,500 mm (Alvares et al., 2013). The soil was classified as Rhodic Hapludox (Soil Survey Staff, 2010) and the physical and chemical soil properties are presented in Table 1.

As described in previous studies (Nascimento et al., 2017; Silva et al., 2019; Ramos et al., 2022), the most representative management systems used by the *Quilombola* community were selected: i) maize cultivation (M1 and M2), citrus-cassava intercropping (T1), citrus monoculture (T2), and pasture (PP1 and PP2). In addition, reference areas without anthropic intervention were selected (NC1 and NC2) near the *Quilombola* management systems. Here, we denominate *Cerradão* as high Cerrado (HC) and *Stricto sensu* as low Cerrado (LC).

The historical management of the sampled sites is shown in Table 2. Briefly, in HC, the M1 area has been managed for 30 years, with the first 20 years based only on the rice/bean/maize crop rotation and the last ten years based on synthetic inputs. The PP1 area has not been managed in the last 15 years and is naturally invaded by grasses without cattle grazing. The T1 area has been cultivated in the last five years with citrus intercropped with cassava. For 21 years, the T1 area was cultivated with grasses and fertilized with cattle manure in continuous grazing.

In LC, the M2 area has been managed for 15 years under grain cultivation with conventional practices of soil tillage. The PP2 area was naturally invaded by grasses without cattle grazing. The T2 area has been cultivated in the last five years with citrus monoculture

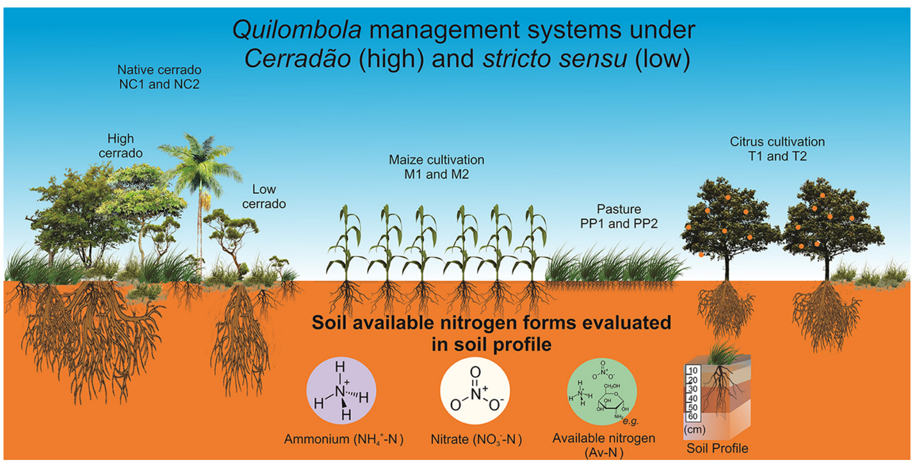

Figure 1 – Schematic representation of the factors evaluated in this study under high (*Cerradão*) and low (*Stricto sensu*) Cerrado phytophysiognomies. The ammonium (NH_4^+-N), nitrate (NO_3^--N) and the available nitrogen (Av-N).

Table 1 – Soil physical and chemical characterization considering 0-10 cm of soil depth in the areas under different *Quilombola* management systems in high (*Cerradão*) and low (*Stricto sensu*) Cerrado phytophysiognomies (adapted from Nascimento et al., 2017 and Silva et al., 2019).

Managements[1]	pH in H_2O	Al^{3+}	Ca^{2+}	Mg^{2+}	H+Al	P	K	m	Silt	Sand	Clay	CEC
		------- $cmol_c\ kg^{-1}$ -------				------ $mg\ dm^{-3}$ ------		%	------- $g\ kg^{-1}$ -------			$cmol_c\ kg^{-1}$
High cerrado (*Cerradão*)												
NC1	5.1	0.55	4.06	1.34	9.0	1.3	148	8.7	410	40	550	3.6
M1	5.9	0.03	4.57	1.28	4.1	8.4	353	0.4	410	40	550	
PP1	4.7	0.64	0.34	0.28	5.9	2.1	118	41.0	280	120	600	
T1	5.8	0.06	6.34	1.95	5.7	3.7	308	0.6	410	40	550	
Low cerrado (*Stricto sensu*)												
NC2	4.7	0.72	0.07	0.19	6.2	0.8	54	11	270	100	630	1.1
M2	5.2	0.10	1.79	1.07	5.4	7.8	79	1.2	270	100	630	
PP2	4.7	0.63	0.33	0.36	7.0	0.9	76	8.0	270	100	630	
T2	5.2	0.19	1.08	0.73	5.5	1.8	186	2.4	270	100	630	

[1]NC1 and NC2 = native Cerrado; M1 and M2 = maize cultivation; PP1and PP2 = pasture; T1 = citrus – cassava intercropping and T2 = citrus monoculture. m = aluminum saturation. CEC = cation exchange capacity.

Table 2 – Characteristics of the study sites. Source: Adapted from Ramos et al. (2022).

Cerrado phytophysiognomy	Management system	Acronym	Area	History
Cerradão (High Cerrado)	Native Cerrado	NC1	-	Remnant of the *Cerradão* used as a reference and without any exploration or anthropic interference.
	Pasture	PP1	1 ha	Area occupied by pastures without soil preparation and fertility management. In the last 15 years, there was no management, thus, *Urochloa decumbens* (Stapf) and *Urochloa brizantha* (Stapf) naturally invaded the location.
	Maize cultivation	M1	1 ha	Area managed for 30 years with planting of grains via conventional practices of minimum soil preparation. Weeds are present, but there is no straw on the soil.
	Citrus-cassava intercropping	T1	0.25 ha	For 21 years, the area has been cultivated with *Urochloa decumbens* (Stapf) Webster, fertilized with cattle manure and the pasture maintained with continuous cattle grazing. Pasture removed and for four years, the area cultivated with tangerine (*Citrus reticulata* L.). Since 2016, the area has been intercropped with cassava (*Manihot esculenta* L.). Mulching preserved in the area composed of fruit remains, leaves, and weeds to ensure that the soil is permanently covered.
Stricto sensu (Low Cerrado)	Native Cerrado	NC2	-	Remnant of Cerrado *Stricto sensu* used as reference and without any exploration or anthropic interference.
	Pasture	PP2	7 ha	Area occupied by pastures, covered by *Urochloa brizantha* (Stapf) and *Urochloa decumbens* (Stapf), which naturally invaded the area.
	Maize cultivation	M2	2 ha	Area managed for 15 years under grain cultivation with conventional practices of soil tillage. In the last ten years, the area has been annually cultivated only with maize. The soil remains permanently uncovered.
	Citrus monoculture	T2	0.5 ha	Area managed for five years with tangerine (*Citrus reticulata* L.) cultivation with conventional minimum soil tillage. *Citrus* is not intercropped with any other crop and the soil remains always uncovered. Weeds in the area were removed and the waste was piled near the crop.

and fertilized with organic compost. Both native areas (NC1 and NC2) were used as references due to the absence of anthropic exploitation or interference.

The soil was sampled in Apr 2014 at six depths (0-10, 10-20, 20-30, 30-40, 40-50 and 50-60 cm). In reference areas (NC1 and NC2) and pasture (PP1 and PP2), a diagonal line was projected and the soil was sampled at every 50 m. In maize cultivation (M1 and M2), the soil was sampled in the plant rows and inter rows, while in citrus plantations (T1 and T2), soil samples were collected in the canopy projection of the citrus trees (Ramos et al., 2022).

Five random points were collected for each management system at each depth, representing the repetitions. We collected 240 composite samples to evaluate eight management systems, six soil depths and five replications. Soil samples were sieved through a 2.0 mm diameter sieve and stored at 4 °C.

Analytical procedures

Available nitrogen forms (Av-N)

Available N forms include organic components of low molecular weight, easily absorbed by plants, as amino acids and amino sugars besides the ammonium and nitrate (Oliveira, 1989). Several chemical extractors were used experimentally to estimate N availability in the soil, which generally shows a high correlation with N uptake by plants (Stanford, 1982; Bremner and Breitenbeck, 1983; Oliveira, 1989; Meneghin et al., 2008).

Test tubes with 2 g of soil, 0.2 g of magnesium oxide (MgO) and 0.1 g of Devarda alloy were submitted to steam distillation (Kjeldahl) using 25 mL of sodium phosphate-borate (Na_3PO_4/borax - pH 11.2 buffer solution). The distillate was collected in a flask containing 10 mL of 0.05 N HCl, until completing 35 mL. In this process, the heating implies N volatilization in the NH_3 form (stemming from amino sugars and N hydrolyses from amines and amides) (Oliveira, 1989). The amount of extracted N was determined by colorimetric spectrophotometry at 440 nm using 1 mL of Nessler's reagent (Meneghin et al., 2008). The readings were compared to the values of a standard solution containing 0, 15, 30, 45, and 60 µg mL^{-1} N (Coser et al., 2016).

Available inorganic nitrogen forms: ammonium (NH_4^+-N) and nitrate (NO_3^--N)

We determined ammonium and nitrate contents starting with a 15 g soil sample and applying the extraction method using 2 mol L^{-1} KCl (Bremner and Keeney, 1965). Again, the ammonium was obtained by steam distillation, collected in an indicator solution of boric acid and then determined by titration with acid of standard normality. Afterward, MgO and Devarda alloy were added to reduce nitrate and nitrite to ammonium (Bremner and Keeney, 1965). In summary, 15 g of soil were mixed with 50 mL of 2 mol L^{-1} KCl. After decanting the soil, the supernatant was filtered and 10 mL of the extract were transferred to test tubes, adding 2 g of

MgO and submitted to steam distillation (Kjeldahl). The distillate was collected in a flask containing 10 mL of 2 % H_3BO_3 until it reached around 30 mL to determine ammonium by titration with 0.05 N H_2SO_4 (standard acid). In the same test tube used in the first distillation to determine ammonium, we added 0.2 g of Devarda alloy, and we used the second distillation and another titration with the standard acid aforementioned to determine the nitrate concentration.

Data analyses

One-way ANOVA followed by Tukey's post hoc tests ($p < 0.05$) were used to assess soil N distribution differences between the *Quilombola* management systems. This approach is only possible when the sites have the same topography and soil type, and the edaphic or climatic conditions differ only in terms of land-use (Merloti et al., 2019). Therefore, this approach was adequate for our study. However, before conducting the ANOVA, the normality and variance homoscedasticity were tested using the *Kolmogorov-Smirnov* and *Hartley* tests, respectively.

The principal component analysis (PCA) was used as a data-reduction tool to select the N form most correlated with each Cerrado phytophysiognomy (Ramette, 2007). For the assumption of multivariate normality, the data were transformed to a log of (C + 1), where (1) is a constant value to avoid negative results and C is the value of the measured variable (Legendre and Legendre, 1998). We compared the *Quilombola* management systems with the reference areas (NC1 and NC2), within each Cerrado vegetation to explore the N form dynamics, using an effect size analysis, which considers a 95 % confidential interval with 1000 bootstrap repetitions (Goedhart, 2016). For this analysis, we used the RStudio Team version 1.2.1335 (R Core Team, 2019).

Results

In general, there was a distinction between high Cerrado (HC) (*Cerradão*) and low Cerrado (LC) (*Stricto sensu*) according to the spatial ordering of the soil N forms. Even though there is partial overlapping in the confidential ellipses, the PCA (Figure 2) shows that only a minority of the samples shared the same composition. The available N (Av-N) correlated more intensively with the HC, while ammonium and nitrate correlated well with the LC (Figure 2). Overall, the *Quilombola* management systems located under HC presented a higher cation exchange capacity (CEC) (3.6 $cmol_c\ kg^{-1}$) when compared to LC (1.1 $cmol_c\ kg^{-1}$).

In the effect size analysis, we compared the management systems (maize, pasture and citrus cultivation) to the native Cerrado (NC1 or NC2) to show these management systems' positive or adverse effects. According to the management system, we

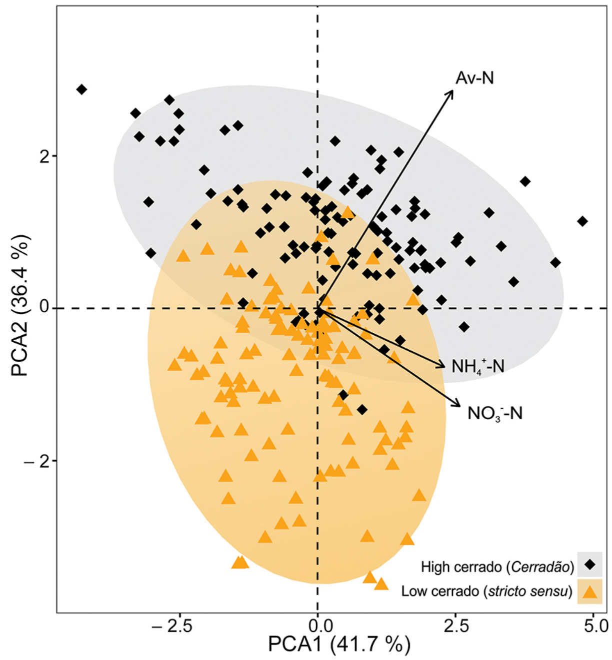

Figure 2 – The principal components analysis for the attributes available nitrogen (Av-N), ammonium (NH_4^+-N) and nitrate (NO_3^--N), considering high (*Cerradão*) and low (*Stricto sensu*) Cerrado phytophysiognomies with 95 % confidential ellipses.

found significant changes in N forms of the Cerrado phytophysiognomy (LC and HC). In the HC, T1 and PP1 were the most contrasting (Figures 3A and 3C) in terms of Av-N and nitrate (NO_3^--N). In the LC, however, there was no pasture management effect (PP2) for all N forms (Figures 3D, 3E, and 3F). On the other hand, comparing with NC2, T2 and M2 showed the most contrasting effects on Av-N and NH_4^+-N contents (Figures 3D and 3E).

Concurrently, there was a positive effect for the T2 system for NH_4^+-N and a negative one for NO_3^--N (Figures 3E and 3F). M2 caused a negative effect for Av-N (Figure 3D) and NH_4^+-N (Figure 3E), but not for NO_3^--N (Figure 3F). Similar results were detected for HC at PP1, which caused a negative effect on Av-N (Figure 3A) and NO_3^--N (Figure 3C), but without an effect on NH_4^+-N (Figure 3B). The systems T1 and M1 affected NH_4^+-N positively (Figure 3B).

In the soil profile, there were no differences ($p > 0.05$) in Av-N among soil layers in all *Quilombola* management systems (M1, M2, PP1, PP2, T1, and T2). However, in the reference sites (NC1 and NC2), there was a decrease in Av-N with increasing soil depths, with the 0-10 cm layer presenting the highest Av-N levels (Table 3). In HC, there was a trend to decrease the NH_4^+-N to the depth of 20-30 cm in M1 and T1, but below that depth, this trend did not occur (Table 3).

On the other hand, in the LC, NH_4^+-N did not decrease along the soil profile in M2 or PP2. T2 presented an increase in NH_4^+-N in the soil profile, ranging from

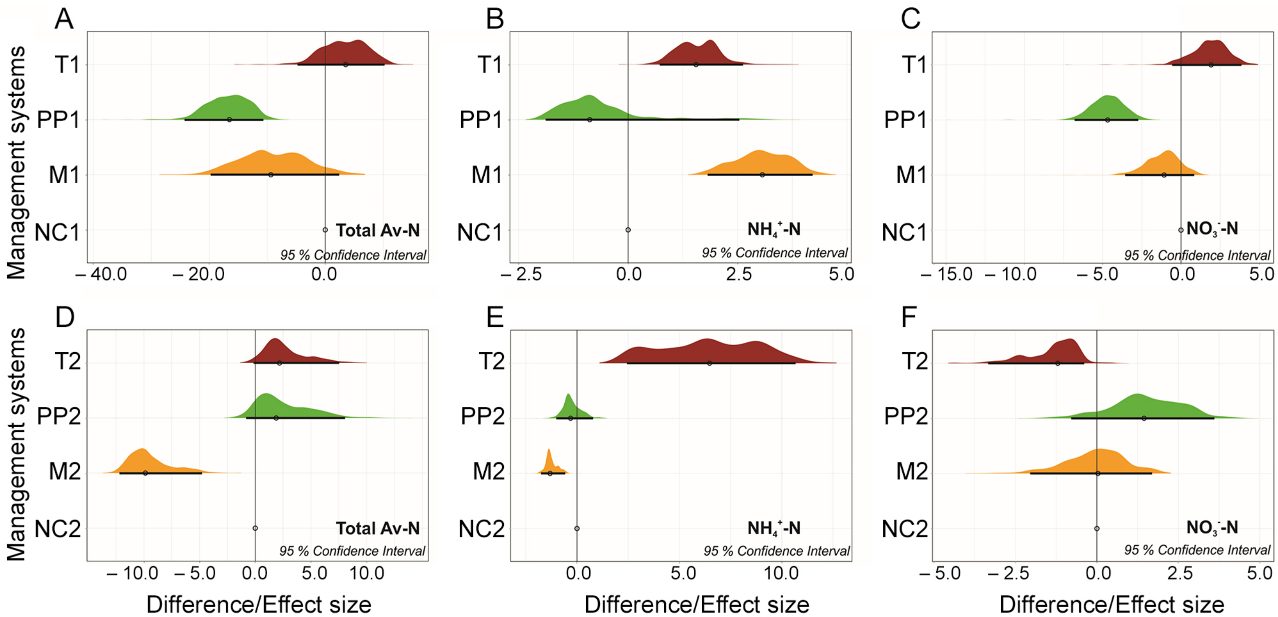

Figure 3 – Difference in effect sizes of management systems compared with native Cerrado (NC1) in high Cerrado (*Cerradão*) (A, B and C) and low Cerrado (*Stricto sensu*) (D, E, and F) based on available soil nitrogen forms. In high Cerrado: (A) available nitrogen, (B) ammonium, (C) nitrate content. In low Cerrado: (D) available nitrogen, (E) ammonium and (F) nitrate content. NC1 and NC2 = native Cerrado; M1 and M2 = maize cultivation; PP1and PP2 = pasture; T1 = citrus – cassava intercropping and T2 citrus monoculture.

Table 3 – Available nitrogen (Av-N), ammonium (NH_4^+-N) and nitrate (NO_3^--N) contents in management systems in high Cerrado (*Cerradão*) and low Cerrado (*Stricto sensu*) and along soil depth.

	Av-N (mg kg^{-1})							
Depth (cm)	High Cerrado (*Cerradão*)				Low Cerrado (*Stricto sensu*)			
	NC1	M1	PP1	T1	NC2	M2	PP2	T2
0-10	109.40 aA	47.45 bA	48.83 bA	59.23 bA	33.71 bA	19.62 cA	47.91 aA	33.33 bA
10-20	68.33 aB	63.20 aA	50.54 aA	63.43 aA	33.52 aAB	22.88 bA	38.02 aA	33.02 aA
20-30	61.33 aBC	53.27 abA	37.33 bA	62.14 aA	27.44 abBC	19.05 bA	32.81 aA	31.06 aA
30-40	53.11 abBC	49.80 abA	38.20 bA	61.21 aA	25.37 abBC	20.67 bA	29.71 aA	33.28 aA
40-50	58.76 aBC	46.92 abA	38.45 bA	64.35 aA	24.97 abBC	19.63 bA	28.36 abA	29.80 aA
50-60	42.32 abC	46.77 abA	39.04 bA	60.55 aA	27.31 aC	23.94 aA	26.87 aA	30.79 aA
	NH_4^+-N (mg kg^{-1})							
Depth (cm)	High Cerrado (*Cerradão*)				Low Cerrado (*Stricto sensu*)			
	NC1	M1	PP1	T1	NC2	M2	PP2	T2
0-10	4.02 bcAB	7.06 aA	3.00 cAB	5.90 abA	2.45 aA	1.26 aA	3.51 aA	6.17 aB
10-20	4.08 aA	5.22 aAB	1.21 bB	3.75 abAB	2.91 bA	0.76 bA	2.95 bA	8.46 aB
20-30	1.19 bBC	4.59 aAB	2.94 abAB	2.66 abB	1.90 abA	1.34 bA	2.07 abA	7.15 aB
30-40	1.03 bC	4.15 aB	5.14 aA	2.89 abB	1.94 bA	0.82 bA	1.01 bA	11.02 aAB
40-50	2.91 aABC	4.05 aB	4.72 aA	4.46 aAB	2.90 bA	1.45 bA	2.99 bA	8.96 aB
50-60	1.60 bABC	6.22 aAB	0.68 bB	4.84 aAB	1.77 bA	1.09 bA	1.24 bA	17.54 aA
	NO_3^--N (mg kg^{-1})							
Depth (cm)	High Cerrado (*Cerradão*)				Low Cerrado (*Stricto sensu*)			
	NC1	M1	PP1	T1	NC2	M2	PP2	T2
0-10	24.57 aA	8.51 cA	9.38 cA	14.00 bAB	12.31 aAB	10.33 aA	11.90 aA	10.12 aA
10-20	16.80 aB	11.76 bA	6.55 cA	17.15 aA	15.88 aA	12.78 abA	14.62 aA	9.47 bA
20-30	13.73 aBC	9.71 abA	6.28 bA	12.31 aAB	13.21 aAB	12.45 aA	14.27 aA	10.00 aA
30-40	11.05 aCD	10.76 aA	6.12 bA	13.17 aAB	10.42 aB	12.36 aA	13.42 aA	11.14 aA
40-50	9.10 aCD	11.54 aA	8.96 aA	11.81 aB	8.88 bB	13.63 aA	10.25 abA	10.44 abA
50-60	6.68 abD	10.25 aA	5.02 bA	10.20 aB	10.44 abB	9.10 abA	13.29 aA	8.81 bA

NC1 and NC2 = native Cerrado; M1 and M2 = maize cultivation; PP1and PP2 = pasture; T1 = citrus – cassava intercropping and T2 = citrus monoculture. Lowercase letters compare the different management systems of a same phytophysiognomy within the same layer at 5 % significance by the Tukey test ($p \leq 0.05$) and uppercase letters compare the layers within the same management system ($p \leq 0.05$).

6.17 mg kg^{-1} (0-10 cm) to 17.54 mg kg^{-1} (50-60 cm). At 0-10 cm soil depth, there was no difference between the management systems (M2, PP2, and T2) and NC2. However, the T2 system showed the highest NH_4^+-N in deeper layers of all management systems and native area (NC2) (Table 3).

Regardless of the Cerrado phytophysiognomy, maize (M1 and M2) and pasture (PP1 and PP2) presented constant NO_3^--N throughout all the layers. However, in the native Cerrado (NC1 and NC2) and intercropped citrus (T1), there was a decrease in NO_3^--N, mainly at the depths of 40-50 and 50-60 cm (Table 3). In the LC, there was no depth effect on NO_3^--N, neither within nor between management systems. However, NO_3^--N decreased at soil depth in NC2, mainly at 30-60 cm (Table 3).

Discussion

Besides the effects of the Cerrado phytophysiognomy on the distribution of available N forms in the soil profile, we also evaluated the magnitude of influence of the management of *Quilombola* systems compared to the native area. Overall, the *Quilombola* management systems under different Cerrado phytophysiognomy (LC and HC) showed apparent differences, which is somewhat expected, as they present contrasting characteristics, such as time of LUC, vegetation type, and farming methods. In addition, N distribution in the soil profile is affected by other factors, such as organic nutrient concentration, soil pH, precipitation, and biological N fixation (Mengel et al., 2001).

More than 90 % of the soil N is present in the organic form and some organic forms (e.g., amino acids, proteins, and amino sugars) are readily available for plants and microorganisms (Mechthild and Doris, 2010; Czaban et al., 2016; Stevens, 2019). Even though the soil has a considerable amount of N in organic forms, mineralization (a process of converting organic compounds into readily available forms) occurs slowly and in small amounts (1 to 3 %) during a crop cycle (Carneiro et al., 2013). Hence, it is essential to understand the dynamics of inorganic N forms in the soil, as they are often the preferred N source in nature and agriculture. Inorganic N forms consist mainly of ammonium (NH_4^+-N) and nitrate (NO_3^--N), which are readily available for uptake by plants or soil microbiota (Li et al., 2014).

For all *Quilombola* management systems, Av-N homogenization was observed in the soil profile while high contents were observed in the top layers of natural areas. Natural areas commonly accumulate organic matter in the topsoil, which could increase of the Av-N content. In contrast, areas that have undergone LUC (e.g., *Cerradão* in pastures or monocultures) tend to decrease the N content in the soil profile (Kizilkaya and Dengiz, 2010; Groppo et al., 2015; Borges et al., 2019; López-Poma et al., 2020; Costa et al., 2020). Maize cultivation under the LC presented the lowest available N content compared to other systems. This finding may be related to the farming practices used, since it is one of the most intensive tillage managements compared to the other systems studied (Green et al., 2007).

NO_3^--N is well recognized as soluble and mobile and it is therefore readily leached into the soil profile (Jadoski et al., 2010), mainly in soils where positive soil charges occur, as in the charge-dependent ones (Alcântara and Camargo, 2005). In this investigation, NO_3^--N was the most constant along the deeper layers in pasture and maize cultivation, regardless of the Cerrado phytophysiognomy, but remained under the top layers in natural areas of Cerrado (NC1 and NC2) and in the citrus-intercropped system (T1). High contents of NO_3^--N and NH_4^+-N have been observed in the superficial layer of natural areas of Cerrado when compared to pasture (López-Poma et al., 2020). These authors also argue that the conversion of native areas (*Cerradão*) to pasture resulted in negative impacts on soil N content. On the other hand, similar contents of NO_3^--N and NH_4^+-N between native areas of Cerrado and pasture in different soil layers have been reported (Frazão et al., 2010).

The available N forms are easily interchangeable, especially for NH_4^+-N and NO_3^--N. Thus, it is sometimes advisable to repeat the experiment for two or more years, as different climatic conditions, for example, may significantly influence it. However, in the present study, we only compared different sites cultivated with varied crops, located very close to each other and exposed to the same climatic interferences.

We consider this investigation pioneering because it shows the distribution of the available N forms in soil under different *Quilombola* management systems, where the agricultural practice is less intensive than in modern agriculture. Overall, we noticed that the dynamics of available N forms varied according to the Cerrado phytophysiognomy, with the prevalence of available N forms in the high Cerrado (*Cerradão*). In contrast, in the low Cerrado (*Stricto sensu*), the inorganic N forms (NH_4^+-N and NO_3^--N) were more prevalent. In addition, although the *Quilombola* family farmers practice less intensive tillage, there was a noticeable impact on the available N dynamics, especially where the management is less conservative, as in maize cultivation, with excessive tillage. On the other hand, the T1, planted with a consortium of legumes, represents an excellent N management while generating income for the producer.

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Authors' Contributions

Conceptualization: Silva AMM, Ramos MLG, Nascimento RSMP, Silva SB, Cardoso EJBN. **Data curation**: Silva AMM, Nascimento RSMP, Silva SB. **Formal analysis**: Silva AMM, Feiler HP. **Funding acquisition**: Ramos MLG, Nascimento RSMP, Cardoso EJBN. **Investigation**: Silva AMM, Ramos MLG, Nascimento RSMP, Silva SB. **Methodology**: Silva AMM, Ramos MLG, Nascimento RSMP, Silva SB. **Project administration**: Ramos MLG, Nascimento RSMP. **Resources**: Ramos MLG, Cardoso EJBN. **Supervision**: Ramos MLG, Nascimento RSMP. **Writing-original draft**: Silva AMM, Ramos MLG, Feiler HP. **Writing-review & editing**: Silva AMM, Ramos MLG, Feiler HP.

References

Alcântara MAK, Camargo AO. 2005. Nitrate adsorption in variable charged soils. Pesquisa Agropecuária Brasileira 40: 369-376 (in Portuguese, with abstract in English). https://doi.org/10.1590/S0100-204X2005000400008

Alvares CA, Stape JL, Sentelhas PC, Gonçalves JLM, Sparovek G. 2013. Köppen's climate classification map for Brazil. Meteorologische Zeitschrift 22: 711-728. https://doi.org/10.1127/0941-2948/2013/0507

Borges LAB, Ramos MLG, Fernandes PM, Carneiro MAC, Silva AMM. 2019. Organic cultivation of sugarcane restores soil organic carbon and nitrogen. Organic Agriculture 9: 435-444. https://doi.org/10.1007/s13165-018-0234-x

Bremner JM, Keeney DR. 1965 Steam-distillation methods for determination of ammonium, nitrate and nitrite. Analytica Chimica Acta 32: 485-495. https://doi.org/10.1016/S0003-2670(00)88973-4

Bremner JM, Breitenbeck GA. 1983. A simple method for determination of ammonium in semimicro-Kjeldahl analysis of soil and plant materials using a block digester. Communications in Soil Science and Plant Analysis 14: 905-914. https://doi.org/10.1080/00103628309367418

Carneiro WJO, Silva CA, Muniz JA, Savian TV. 2013. Nitrogen mineralization in latosols fertilized with organic residues. Revista Brasileira Ciência do Solo 37: 715-725 (in Portuguese, with abstract in English). https://doi.org/10.1590/S0100-06832013000300018

Czaban W, Jämtgård S, Näsholm T, Rasmussen J, Nicolaisen M, Fomsgaard IS. 2016. Direct acquisition of organic N by white clover even in the presence of inorganic N. Plant and Soil 407: 91-107. https://doi:10.1007/s11104-016-2896-z

Colli GR, Vieira CR, Dianese JC. 2020. Biodiversity and conservation of the Cerrado: recent advances and old challenges. Biodiversity and Conservation 29: 1465-1475. https://doi.org/10.1007/s10531-020-01967-x

Coser TR, Ramos MLG, Figueiredo CC, Carvalho AM, Cavalcante E, Moreira MKR, et al. 2016. Soil microbiological properties and available nitrogen for corn in monoculture and intercropped with forage. Pesquisa Agropecuária Brasileira 51: 1660-1667. https://doi.org/10.1590/s0100-204x2016000900066

Costa AA, Dias BO, Fraga VS, Santana CC, Silva N. 2020. Carbon and nitrogen stocks in soils under different forms of use in the Cerrado. Revista Brasileira de Engenharia Agrícola e Ambiental 24: 528-533. https://doi.org/10.1590/1807-1929/agriambi.v24n8p528-533

Dias FPM, Hübner R, Nunes FJ, Leandro WM, Xavier FAS. 2019. Effects of land-use change on chemical attributes of a Ferralsol in Brazilian Cerrado. Catena 177: 180-188. https://doi.org/10.1016/j.catena.2019.02.016

Eiten G. 1972. The Cerrado vegetation of Brazil. Botanical Review 38: 201-341. https://doi.org/10.1007/BF02859158

Felfili JM, Fagg CW. 2007. Floristic composition, diversity and structure of the "cerrado" *sensu stricto* on rocky soils in northern Goiás and southern Tocantins, Brazil. Revista Brasileira de Botânica 30: 375-385. https://doi.org/10.1590/S0100-84042007000300004

Frazão LA, Piccolo MC, Feigl BJ, Cerri CC, Cerri CEP. 2010. Inorganic nitrogen, microbial biomass and microbial activity of a sandy Brazilian Cerrado soil under different land uses. Agriculture, Ecosystems & Environment 135: 161-167. https://doi.org/10.1016/j.agee.2009.09.003

Green VS, Stott DE, Cruz JC, Curi N. 2007. Tillage impacts on soil biological activity and aggregation in a Brazilian Cerrado Oxisol. Soil and Tillage Research 92: 114-121. https://doi.org/10.1016/j.still.2006.01.004

Groppo JD, Lins SRM, Camargo PB, Assad ED, Pinto HS, Martins SC, et al. 2015. Changes in soil carbon, nitrogen, and phosphorus due to land-use changes in Brazil. Biogeosciences 12: 4765-4780. https://doi.org/10.5194/bg-12-4765-2015

Goedhart J. 2016. Calculation of a distribution free estimate of effect size and confidence intervals using VBA/Excel. BioRxiv e073999. https://doi.org/10.1101/073999

Jadoski SO, Saito LR, Prado C, Lopes EC, Sales LLSR. 2010. Características da lixiviação de nitrato em áreas de agricultura intensiva. Pesquisa Aplicada & Agrotecnologia 3: 193-200. (in Portuguese, with abstract in Spanish).

Kizilkaya R, Dengiz O. 2010. Variation of land use and land cover effects on some soil physico-chemical characteristics and soil enzyme activity. Zemdirbyste-Agriculture 97: 15-24.

Kohler F, Brondizio ES. 2017. Considering the needs of indigenous and local populations in conservation programs. Conservation Biology 31: 245-251. https://doi.org/10.1111/cobi.12843

Legendre P, Legendre L. 1998. Numerical Ecology. Elsevier, Amsterdam, Netherlands.

Li S, Wang Z, Miao Y, Li S. 2014. Soil organic nitrogen and its contribution to crop production. Journal of Integrative Agriculture 13: 2061-2080. https://doi.org/10.1016/S2095-3119(14)60847-9

López-Poma R, Pivello VR, Brito GS, Bautista S. 2020. Impact of the conversion of Brazilian woodland savanna (*cerradão*) to pasture and *Eucalyptus* plantations on soil nitrogen mineralization. Science of the Total Environment 704: e135397. https://doi.org/10.1016/j.scitotenv.2019.135397

Mechthild T, Doris R. 2010. Uptake and partitioning of amino acids and peptides. Molecular Plant 3: 997-1011. https://doi.org/10.1093/mp/ssq047

Meneghin MFS, Ramos MLG, Oliveira SA, Ribeiro Junior WQ, Amábile RF. 2008. Soil nitrogen availability for wheat in a Cerrado Red Latosol. Revista Brasileira de Ciência do Solo 32: 1941-1948 (in Portuguese, with abstract in English). https://doi.org/10.1590/S0100-06832008000500015

Mengel K, Kirkby EA, Kosegarten H, Appel T. 2001. Nitrogen. p. 397-434. In: Mengel K, Kirkby EA, Kosegarten H, Appel T. eds. Principles of plant nutrition. Springer, Dordrecht, Netherlands. https://doi.org/10.1007/978-94-010-1009-2_7

Merloti LF, Mendes LW, Pedrinho A, Souza LF, Ferrari BM, Tsai SM. 2019. Forest-to-agriculture conversion in Amazon drives soil microbial communities and N-cycle. Soil Biology and Biochemistry 137: 107567. https://doi.org/10.1016/j.soilbio.2019.107567

Nascimento RSMP, Ramos MLG, Figueiredo CC, Silva AMM, Silva SB, Batistella G. 2017. Soil organic matter pools under management systems in Quilombola Territory in Brazilian Cerrado. Revista Brasileira de Engenharia Agrícola e Ambiental 21: 254-260. https://doi.org/10.1590/1807-1929/agriambi.v21n4p254-260

Oliveira SA. 1989. Assessment of nitrogen availability in the soil = Avaliação da disponibilidade de nitrogênio no solo. Pesquisa Agropecuária Brasileira 24: 31-48 (in Portuguese).

Ramette A. 2007. Multivariate analyses in microbial ecology. FEMS Microbial Ecology 62: 142-160. https://doi.org/10.1111/j.1574-6941.2007.00375.x

Ramos MLG, Nascimento RSMP, Silva AMM, Silva SB, Oliveira-Júnior MP. 2022. Carbon and nitrogen stocks in cultivation systems of a *Quilombola* community in the Brazilian Cerrado. Regional Environmental Change 22: 81. https://doi.org/10.1007/s10113-022-01941-z

Ratter JA, Ribeiro JF, Bridgewater S. 1997. The Brazilian Cerrado vegetation and threats to its biodiversity. Annals of Botany 80: 223-230. https://doi.org/10.1006/anbo.1997.0469

Silva AMM, Ramos MLG, Nascimento RSMP, Silva AN, Silva SB, Cardoso EJBN, et al. 2019. Soil quality indicators under management systems in a *Quilombola* community in the Brazilian Cerrado. Scientia Agricola 76: 518-526. https://doi.org/10.1590/1678-992x-2018-0008

Soil Survey Staff. 2010. Keys to Soil Taxonomy. 11ed. USDA-NRCS, Washington, DC, USA.

Stanford G. 1982. Assessment of soil nitrogen availability. p. 651-688. In: Stevenson FJ. Nitrogen in agricultural soils. ASA-SSSA, Madison, WI, USA.

Stevens CJ. 2019. Nitrogen in the environment. Science 363: 578-580. https://doi.org/10.1126/science.aav8215