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NUTRIENT CYCLING AND SOIL QUALITY IN THREATENED VEREDAS IN TWO PROTECTED AREAS OF THE BRAZILIAN CERRADO

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Veredas are humid environments of significant importance for the Brazilian Cerrado. Understanding soil quality and ecological processes between the soil and vegetation in veredas can provide insights into ecosystem dynamics. This study was aimed to assess litter deposition and decomposition, as well as soil quality, including chemical, physical, and microbiological attributes, in two threatened veredas at various stages of conservation in Brazil. The research was conducted in Almescla (a preserved vereda) within the Environmental Protection Area of the River Pandeiros, and Peruaçu (a degraded vereda) located at the Veredas do Peruaçu State Park. Litter deposition was measured using collectors, and decomposition was assessed with litter bags. Soil granulometry, carbon and nutrient contents, and soil microbial biomass were also evaluated to a depth of 20 cm. The litter production was higher in Peruaçu, with the leaf fraction accounting for more than 70% of the total in both studied areas. The decomposition constant (kc) was higher in Almescla vereda. Nutrient concentrations followed a decreasing order of Ca > N > K > Mg > S > P in both areas. Peruaçu vereda exhibited higher levels of clay, available P, and Ca. Microbial carbon, total organic carbon, microbial quotient, and carbon stock were higher in Almescla, whereas the metabolic quotient was higher in Peruaçu. Our results suggest that the degradation of vereda ecosystems may lead to changes in nutrient cycling, with reduced litter deposition and decreased carbon storage.

Key words: carbon stock, litter decomposition, litter production, nutrient return, soil fertility, soil microorganisms

Introduction

Veredas, also known as palm swamps, are distinctive phytophysiognomies found within the Brazilian Cerrado, typically situated near watercourses (Nunes et al., 2022; Sales et al., 2023). They are commonly bordered by neotropical savannas (cerrado) or grasslands (campo limpo) and exhibit difference in back zone and middle zone based on drainage characteristics (Ribeiro & Walter, 2008). The back zone is comprised of organic soil with high water saturation, while the middle has varying levels of soil moisture and can be divided into a wet middle zone and a dry middle zone (Nunes et al., 2022). The wet middle zone has soil saturated with water almost year-round, whereas the dry middle zone has got lighter soil and improved drainage (Araújo et al., 2002). The vegetation within veredas is typically sparse in the middle zone and may feature hygrophilous forest in the deeper zones (Carvalho, 1991; Guimarães et al., 2002). Vereda ecosystems provide several crucial functions within the Cerrado (Sales et al., 2023). They act as significant carbon reservoirs (Soares et al., 2015) and play a vital role in regulating water resources (Bahia et al., 2009) by storing water in their peat soils for much of the year (Ribeiro & Walter, 2008; Veloso et al., 2018). There is evidence that vereda soils contain twice as much carbon and organic matter compared to neotropical savanna phytophysiognomies (Brito et al., 2020).

Despite their significant ecological importance, vereda areas have faced considerable anthropogenic pressure in recent years (Guimarães et al., 2017), including drainage, cultivation, deforestation, and fires, among others, leading to severe degradation processes (Nunes et al., 2022). The degradation of wetlands can alter their vegetation structure and consequently the ecosystem services associated with them, such as water provision and carbon storage (Hergoualc'h et al., 2020). Recent evidence indicates that many Brazilian veredas are undergoing drying processes, due to changes in land use and climate alterations (Sales et al., 2023), which can significantly impact their soil characteristics (Ávila et al., 2016), vegetation structure (Nunes et al., 2022) and associated fauna (Araújo et al., 2024). For this reason, studying soil characteristics and nutrient cycling is crucial in these ecosystems.

Changes in soil quality in wetlands can significantly impact their structure and function (Gomes et al., 2022; Li et al., 2023), as species within these ecosystems are adapted to their unique edaphic conditions (Silva et al., 2018). The degradation of these environments, along with an increase in available nitrate, ammonium, and phosphorus, can result in the loss of indicator species (Huang et al., 2012). Organic soils found in veredas are poorly developed and exhibit water saturation coupled with high levels of organic material (Sales et al., 2023). These characteristics hinder the mineralisation process due to the limited oxygenation (Santos et al., 2018). However, drainage of such soils alters the anaerobic conditions of the system, thereby impacting its chemical, physical, and biological properties (Valladares et al., 2008; Singh & Gupta, 2018). Among these attributes, the microbiological component is particularly dynamic and exhibits rapid responses to changes, making it a reliable indicator of soil quality (Martins et al., 2018; Sales et al., 2023).

In addition to soil characteristics, nutrient cycling plays a very important role in the dynamics of plant ecosystems. The nutrient cycle comprises three main components, namely the geochemical cycle, involving the entry and exit of nutrients from the ecosystem, the biogeochemical cycle, which encompasses interactions solely among plants, and the biochemical cycle, which entails the translocation of nutrients within plants (Johnson & Turner, 2019). In this context, litter serves as the primary source of nutrients in the soil, and its decomposition plays a crucial role in nutrient cycling and soil fertilisation (Silva et al., 2018), establishing a vital connection between plants and the soil (Xiang et al., 2018). Thus, assessing litter production, decomposition, and nutrient cycling in the environment provides valuable insights into vegetation productivity and nutrient return (Clark et al., 2001; Almeida et al., 2015).

Some studies have shown that factors such as altitude, latitude, soil type, climate attributes, vegetation composition, and structure can influence litter production (Parsons et al., 2014; Becker et al., 2015). The decomposition rates are influenced by the quality of the material, physicochemical environment, and decomposing organisms (Aerts, 1997; Silva et al., 2018). Additionally, the nutrient concentration in litter can vary depending on climate, species composition, and soil properties. Anthropogenic disturbances can impact litter and soil processes, for example, by reducing litter deposition and altering nutrient concentrations in the soil (Erfani et al., 2017).

Understanding the soil quality and ecological processes between soil and vegetation in veredas is essential for comprehending ecosystem functioning and devising strategies for ecosystem preservation and restoration. Therefore, this study was aimed to assess the soil quality through chemical, physical, and microbiological attributes, as well as litter deposition and decomposition, in two threatened veredas at various conservation stages in Brazil. We formulated two hypotheses: (i) degradation of veredas affect litter deposition patterns, alters decomposition processes, and modifies nutrient cycling; (ii) degraded veredas exhibit altered chemical and physical soil attributes, leading to disturbances in the microbial community and negatively impacting carbon stocks. In this regard, our expectations are that (i) degraded veredas will have lower litter deposition and its components, and (ii) they will also have nutrient-poor soils with lower organic matter content.

Material and Methods

Study area

This study was conducted in two Protected Areas situated in the north of Minas Gerais State, Brazil (Fig. 1). Both studied Protected Areas are situated in a region predominantly characterised by *Aw* climate, according to the Köpen classification (Alvares et al., 2013), with distinctly dry (May to and September) and rainy (October to April) seasons (Fig. 2). The soils in these areas are classified as Organosols and Gleysols (Ramos et al., 2006).

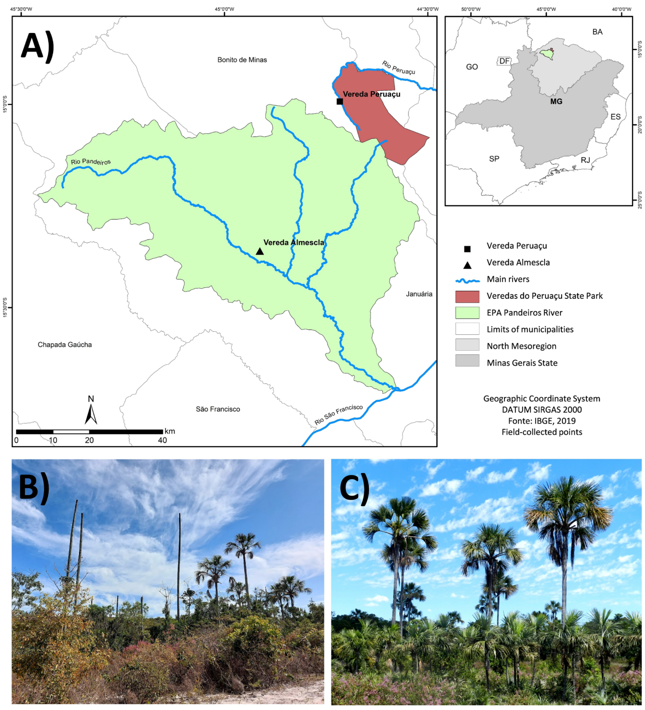

Fig. 1. The location of the study areas (A), namely Vereda Peruaçu (B) within the Veredas do Peruaçu State Park, and Vereda Almescla (C) within the Environmental Protection Area of the River Pandeiros in Minas Gerais State, Brazil.

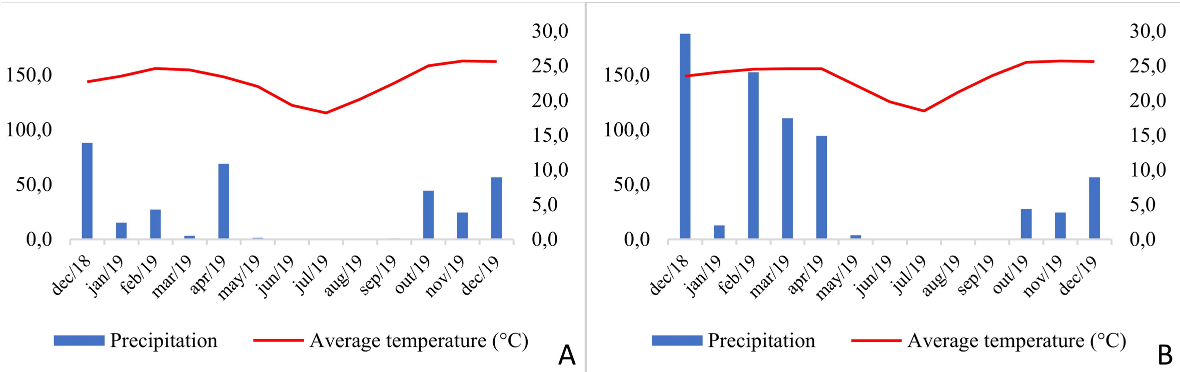

Fig. 2. Climatic data for the year 2019 in the studied areas located in the Veredas do Peruaçu State Park and Environmental Protection Area of the River Pandeiros, Minas Gerais State, Brazil. Designations: A – preserved vereda (Vereda Almescla); B – degraded vereda (Vereda Peruaçu).

The first area is the Environmental Protection Area (EPA) of the River Pandeiros, where the Almescla vereda was sampled (15.360277° S, 44.912500° W). The Almescla extends for 6 km and is located in an area with an average altitude of 640 m a.s.l. Climatic data indicate an average temperature of 22.2°C and an average annual precipitation of 1073 mm (Fig. 2). This area is considered to be well-conserved, with dense vegetation and a high-water table in the deep zone. Despite the presence of livestock and small crops along the Almescla, the area still appears to be in good conservation conditions.

The second Protected Area is the Veredas do Peruaçu State Park, where the Peruaçu vereda was sampled (14.992222° S, 44.715555° W). Vereda do Peruaçu has an approximate length of 6 km and an average altitude of 700 m a.s.l. The average annual temperature is around 22.7°C, and the annual precipitation is approximately 1008 mm (Fig. 2). This vereda exhibits higher signs of environmental degradation. Prior to the establishment of the Veredas do Peruaçu State Park, extensive areas were used for *Eucalyptus* plantations. After creation of the Veredas do Peruaçu State Park, these areas were abandoned, leading to natural regeneration processes. Additionally, *Eucalyptus* cultivation occurred outside the Veredas do Peruaçu State Park boundaries in the recharge areas of the vereda in 2009/2010. Subsequently, the region experienced a prolonged period of drought in 2012–2016. These events may have contributed to the drying up of the veredas and the River Peruaçu, leading to increased intensity and frequency of forest fires and exacerbating degradation processes. Within the Peruaçu area, there is no water table exudation, and numerous dead trees and palms can be observed, with replacement by typical cerrado vegetation (Nunes et al., 2022). In this area, the vegetation in the bottomlands is open over large extensions.

Physicochemical soil attributes

In the longitudinal direction of the vereda, 30 plots measuring 20 × 10 m were established in the back zone in each area, resulting in a total area of 200 m^2 for each plot, with a spacing of 150 m between plots. For soil evaluation, samples were collected in 30 plots along each vereda, at a depth of 0–20 cm using an auger. Each composite sample comprised five individual samples collected from the vertices and centre of each plot, which were then homogenised to create a single sample. These samples were air-dried, sieved, and sent to the laboratory for chemical and physical analyses following the methods proposed by Teixeira et al. (2017).

The hydrogen ion potential (pH) was measured in a suspension of soil in water and a $CaCl_2$ solution with an electrode. The cation exchange capacity (CEC) was obtained by the extraction method with a HCl solution. Determination of exchangeable aluminium by extraction with KCl solution and determination with NaOH, calcium, and magnesium solutions by extraction with KCl and complexometric determination with indicators have been performed. Potassium was determined by extraction with a hydrochloric acid solution and subsequent flame spectrophotometry, and phosphorus by reduction with ascorbic acid, and determination by spectrophotometry. The exchangeable acidity (H + Al) was determined using a solution with KCl and subsequent titration with NaOH solution. Base saturation (V%) and aluminium saturation (m%) were calculated according to the expression suggested by Teixeira et al. (2017). The particle size analysis was performed using the pipette method, after the addition of a chemical dispersant; the sand was measured by sieving, clay was kiln dried and weighed, and silt was calculated with percentage complementation (Teixeira et al., 2017).

Soil microbiological attributes

The evaluation of microbiological attributes was carried out in 12 plots per studied area, where mini trenches were opened for a soil collection at depths of 0–10 cm and 10–20 cm. After being collected, the soil was placed in plastic bags with a respirator and stored in a refrigerator. Then, it was passed through a 2-mm sieve, and plant and animal residues were removed by manual collection. After this procedure, the analyses were carried out.

To evaluate the Total Organic Carbon (TOC), part of the exposed soil was used for natural drying, which was then ground in a porcelain grain and sieved in a 0.167-mm sieve. The soil was digested in a solution of $K_2Cr_2O_7$ and H_2SO_4 and titrated with ammoniacal ferrous sulphate (Yeomans & Bremner, 1988). For the analysis of other microbiological attributes, part of the soil was incubated in an airtight system and kept in the dark for seven days. Microbial carbon (C-mic) was calculated using the fumigation-extraction methodology adapted by Silva et al. (2007a). The C-mic was calculated from the difference between fumigated and non-fumigated samples, using a correction factor (kc) of 0.33 (Sparling & West, 1988). In the hermetic system, a NaOH solution was used for precipitation of the CO_2 produced by the microorganisms to evaluate the basal soil respiration (BSR), and the base excess was obtained by titration with HCl adapted by Silva et al. (2007b).

From the data obtained, quotients for indirect evaluation of the microbiota present in the soil were calculated, the microbial quotient (qMIC), which is the ratio between C-mic and TOC, represents the amount of soil microbial biomass due to the amount of carbon present (Anderson 1994) and the metabolic quotient (qCO_2), the relationship between BSR and C-mic, indicating soil microbial activity (Anderson & Domsch, 1993). In the field, we collected undisturbed soil samples using the same plots and mini trenches, with the aid of volumetric rings, to obtain density at depths of 0–10 cm and 10–20 cm. Multiplying the TOC contents (%) by the soil density ($g \times cm^{-3}$) and sampled depth (cm), the soil carbon stock (SCS, $mg \times km^2$) was obtained using the methodology proposed by Fidalgo et al. (2007).

Litter deposition

To evaluate litter production, a collector was arbitrarily distributed at the centre of each plot. The collectors had dimensions of 50 × 50 cm, made with 1-mm nylon mesh and PVC pipes, totalling an area of 0.25 m^2, and installed 30 cm above the ground. Sampling was performed monthly for a period of one year (December 2018 to November 2019), and all the intercepted material was collected, taken to the laboratory, and stratified into leaf, reproductive material, stem, and debris fractions. The material was subsequently taken to the forced circulation oven, where it was monitored at an interval of two days, and removed after obtaining a constant weight, using a precision scale (Arato et al., 2003), and the biomass was estimated per 0.01 km^2.

Litter decomposition

To carry out this experiment, the litter was collected from four points of the plots on each vereda, separated into 50-g portions, and accommodated in 1-mm mesh nylon bags (litterbags), with dimensions of 20 × 10 cm. To conduct this experiment, 12 litterbags were arbitrarily placed in each plot. Monthly, one litterbag per plot was removed and taken to the Vegetal Ecology laboratory. In the laboratory, litterbags were washed in running water, dried in an oven at 60°C, for 48 h, and weighed again. From these procedures, we obtained the decomposition constant by mass loss, proposed by Thomas & Asakawa (1993), and the half-life time by the equation proposed by Costa & Atapattu (2001).

Nutrients from burlap

As the leaves are the most representative fraction, only this one was used for the analysis of macronutrients presented in the litter. For this purpose, the dry leaves were ground in a knife mill and sent to the analysis laboratory, where values of P, K, Ca, Mg, S, and N were evaluated according to the methodology proposed by Carmo et al. (2000). The obtained values were extrapolated according to the annual production of this fraction.

Data analyses

To compare the parameters of organic matter deposition between the studied veredas, generalised linear models (GLMs) were used. In these models, the types of veredas (Peruaçu vs. Almescla) and the depth of the soil (0–10 cm and 10–20 cm) were used as explanatory variables, and various microbiological attributes (TOC, C-mic, BSR, qCO2, qMIC), and soil carbon stock (SCS) were the response variables. GLMs were used to compare various soil parameters (pH, Ca, Mg, K, P, Al, H + Al, CTC, V%, m%, and particle size), deposition fractions (leaf, stem, reproductive material, debris, and total) and decomposition data (k and half-life) between the two studied veredas. All GLMs were checked for residual distribution and Gaussian error distribution was used. To analyse the monthly deposition of various litter fractions we used generalised linear mixed-effects models (GLMMs). These models employed the plots as random effect explanatory variables and the months as fixed-effect explanatory variables. The lme4 package (Bates et al., 2015) was used for constructing the GLMMs. All analyses were performed using the glm function from the base-R/stats package in R software ver. 3.6.1 (R Core Team, 2020).

Results

The soil texture evaluation revealed that the Almescla vereda presented a sandy loam soil and Peruaçu a sandy clay loam. The amount of clay in Peruaçu was higher than in Almescla. However, no difference was found between the other texture fractions, silt, and sand (Table 1). The average density of the soil in the Peruaçu vereda was, respectively, 1.08 g × cm^{-3} and 1.31 g × cm^{-3} at depths of 0–10 cm and 10–20 cm, while in the Almescla vereda it was 1.12 g × cm^{-3} and 1.40 g × cm^{-3} at depths of 0–10 cm and 10–20 cm, respectively (Table 1).

The values of P and Ca were higher in the Peruaçu vereda (Table 2). However, no statistical differences were observed for the other evaluated attributes, namely pH, Mg, K, Al, H + Al, CTC, V%, and m% (Table 2). Regarding microbiological attributes, Cmic and SCS were higher in Almescla, while qCO_2 was higher in Peruaçu (Table 3). For the other attributes (BSR, qMIC, and TOC) no statistical differences were observed. Comparing the SCS of the two studied areas, Peruaçu has a decrease of 31.46% of C, which corresponds to almost 0.0018 mg (C) × km^2 lost to the atmosphere, only in the 0–10-cm layer of the soil (Table 3).

As for the total litter production in one year, the Peruaçu vereda had greater deposition than Almescla, as well as the reproductive material and stem fractions. The debris fraction was higher in Almescla and there was no statistical difference in the production of the leaf fraction between the two veredas (Table 4). Among the fractions, for both areas, the leaf was the most representative, and debris was the one with the least representation. However, in Peruaçu, reproductive material was superior to stem, while in Almescla, the stem was superior.

Regarding monthly deposition (Fig. 3), greater total and leaf fraction depositions were found in the Almescla vereda in September, with no similar event being found in Peruaçu vereda. A higher reproductive material deposition pattern was also observed in Almescla vereda in the final dry and rainy months, while in Peruaçu vereda the highest production of this fraction was found at the end of the rainy season, extending until its beginning.

Table 1. Mean and standard deviation values of the soil texture (clay, sand, and silt) and soil density in the Peruaçu (degraded) and Almescla (preserved) veredas located in the Veredas do Peruaçu State Park and Environmental Protection Area of the River Pandeiros, Minas Gerais State, Brazil

Soil physical attributes	Peruaçu (degraded) vereda		Almescla (preserved) vereda		p-value
	Average	SD	Average	SD	
Clay (%)	22.83	5.55	14.85	8.08	< 0.05
Sand (%)	52.75	17.75	60.75	31.55	0.19
Silt (%)	24.41	14.86	24.40	22.34	1.00
Density (g × cm^{-3}) at 0–10 cm	1.08	0.18	1.12	0.17	0.59
Density (g × cm^{-3}) at 10–20 cm	1.31	0.17	1.40	0.25	0.41

Note: SD – standard deviation.

Table 2. Chemical attributes of soil in the Vereda Peruaçu (degraded) and Vereda Almescla (preserved) located in the Veredas do Peruaçu State Park, and Environmental Protection Area of the River Pandeiros, Minas Gerais State, Brazil

Soil fertility	Peruaçu (degraded) vereda		Almescla (preserved) vereda		p-value
	Mean	SD	Mean	SD	
pH in water	4.43	0.45	4.51	0.41	0.48
P Mehlich (mg × dm^{-3})	16.49	10.19	10.26	6.13	< 0.05
Ca ($cmol_c$ × dm^{-3})	3.31	4.82	1.15	1.37	0.02
Mg ($cmol_c$ × dm^{-3})	0.24	0.19	0.20	0.12	0.37
K (mg × dm^{-3})	97.03	52.31	93.19	45.13	0.76
Al ($cmol_c$ × dm^{-3})	2.10	1.40	2.05	1.48	0.91
H+Al ($cmol_c$ × dm^{-3})	16.46	5.79	14.91	9.21	0.44
CTC ($cmol_c$ × dm^{-3})	20.26	7.01	16.50	9.23	0.08
V%	17.67	18.20	13.03	14.63	0.28
m%	50.13	34.52	56.93	29.34	0.41

Note: SD – standard deviation.

Table 3. Microbiological attributes in the 0–10 cm and 10–20 cm soil layers in the Vereda Peruaçu (degraded) and Vereda Almescla (preserved) located in the Veredas do Peruaçu State Park, and Environmental Protection Area of the River Pandeiros, Minas Gerais State, Brazil

Attributes	Depth	Peruaçu (degraded) vereda		Almescla (preserved) vereda		p-value (area)	p-value (depth)
		Mean	SD	Mean	SD		
BSR (mgC-CO_2 × kg × soil^{-1} × hour^{-1})	0–10 cm	0.09	0.04	0.10	0.05	0.66	0.10
	10–20 cm	0.08	0.03	0.08	0.03		
C-mic (Mg × kg^{-1})	0–10 cm	92.94	75.79	175.43	118.24	< 0.05	0.06
	10–20 cm	65.39	40.63	114.59	74.27		
qCO2	0–10 cm	1.99	1.87	0.87	0.66	0.01	0.51
	10–20 cm	1.50	0.98	0.89	0.52		
TOC (%)	0–10 cm	3.99	2.29	5.63	3.04	0.02	0.29
	10–20 cm	3.12	1.63	3.91	2.83		
qMIC	0–10 cm	0.40	0.39	0.38	0.30	0.40	0.30
	10–20 cm	0.21	0.13	0.39	0.24		
SCS (mg × km^2)	0–10 cm	0.0039	0.0018	0.0057	0.0028	0.07	0.06
	10–20 cm	0.0038	0.0016	0.0045	0.0028		

Note: BSR – basal soil respiration, C-mic – microbial carbon, qCO2 – metabolic quotient, TOC – total organic carbon, qMIC – microbial quotient, SCS – soil carbon stock; SD – standard deviation.

Table 4. The litter production in leaf, reproductive material, stem, debris, and total fractions (in mg × km^2 × year^{-1}) in the Veredas do Peruaçu State Park, and Environmental Protection Area of the River Pandeiros, Minas Gerais State, Brazil

Area	Leaf		Reproductive Material		Stalk		Debris		Total	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Peruaçu (degraded)	0.00382	0.00143	0.00075	0.00076	0.00068	0.00045	0.00019	0.00011	5.00044	0.00201
Almescla (preserved)	0.00323	0.00143	0.00031	0.00032	0.30007	0.00021	0.00027	0.00015	0.00382	0.00143
p-value	0.11		< 0.05		< 0.05		0.02		0.01	

Note: SD – standard deviation.

In Almescla vereda, in the wettest month (February) and the final month of the dry season (September), the highest production of the stem fraction was observed (Fig. 3). However, in Peruaçu vereda, a clear pattern of deposition of this fraction was not found. In Almescla vereda, debris had higher deposition in the month with the highest rainfall and the final months of drought. At the same time, in Peruaçu vereda, a clear pattern was not observed, and the highest debris deposition was observed in several months (Fig. 3).

After one year of evaluation, the remaining mass of litterbags at Almescla vereda was 54.18% and at Peruaçu vereda it was 65.10%. The mean k-value, obtained for Peruaçu vereda, was 0.001224 ± 0.001289 g × g^{-1} × day^{-1}, or 0.45 g × g^{-1} × year^{-1} and the half-life time was 566 days. These values were lower than the k value found for Almescla vereda, (0.001871 ± 0.000632 g × g^{-1} × day^{-1} or 0.66 g × g^{-1} × year^{-1}), with the half-life of 370 days.

Regarding the number of macronutrients found in the leaves of litter intercepted during one year, their higher amounts were observed in the following order: Ca > N > K > Mg > S > P (Table 5). As for the deposition and the state of degradation of the studied veredas, the contents of N, S, and P were higher in the degraded Peruaçu vereda, and the other nutrients did not show significant differences for both studied areas (Table 5).

Discussion

In general, the obtained data indicate a low nutrient content and high soil acidity in the two evaluated veredas, which differs from the findings of previous studies conducted in vereda areas (Veloso et al., 2018; Brito et al., 2020). Organosols, typical of veredas, act as carbon reservoirs, containing plant material in various stages of decomposition, and exhibit high acidity, cation exchange capacity (CTC), and low base saturation (Soares et al., 2015; Santos et al., 2018). The anaerobic conditions of these soils inhibit mineralisation, but drainage promotes degradation (Santos et al., 2018). Studies by Hergoualc'h et al. (2020) also found higher calcium (Ca) content in areas with the highest degradation index. Switzer et al. (2012) observed that pH, Ca, and magnesium (Mg) levels in the soil increased after burning. It is possible that the less sandy texture in degraded veredas may have contributed to a higher concentration of Ca and phosphorus (P) in this environment (Centeno et al., 2017). According to Ewing et al. (2012), changes in soil chemical properties can impede regeneration in moist environments such as veredas, where natural vegetation is adapted to poor soils with high water saturation.

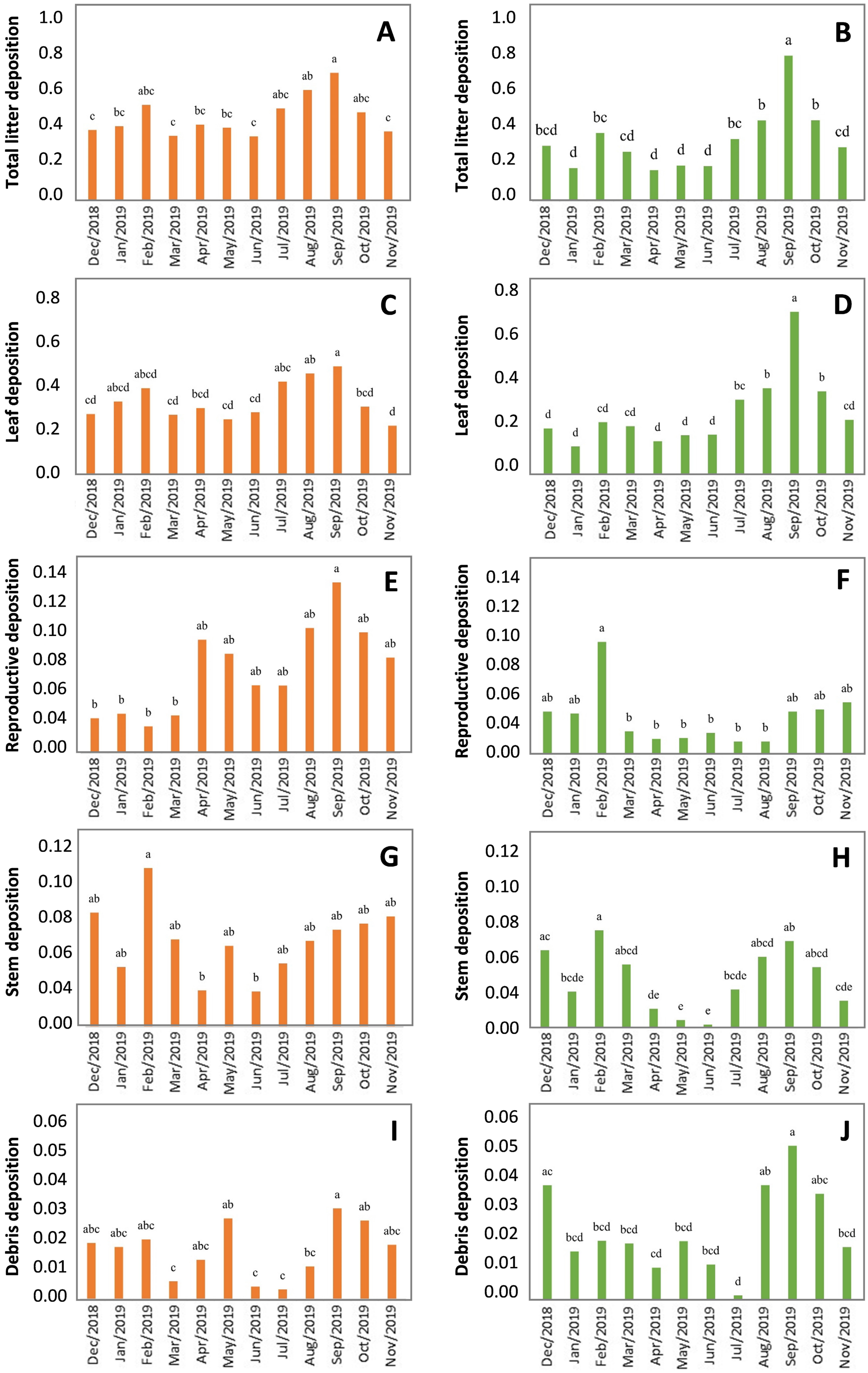

Fig. 3. Monthly litter deposition from December 2018 to November 2019 in the Vereda Peruaçu (degraded) and Vereda Almescla (preserved) located in the Veredas do Peruaçu State Park and Environmental Protection Area of the River Pandeiros, Minas Gerais State, Brazil. Values are presented in mg × km^2 × month^{-1} × 10^4. Designations: A – total litter deposition in Peruaçu vereda; B – total litter deposition in Almescla vereda; C – deposition of the leaf fraction in Peruaçu vereda; D – deposition of the leaf fraction in Almescla vereda; E – deposition of the reproductive material fraction in Peruaçu vereda; F – deposition of the reproductive material fraction in Almescla vereda; G – deposition of the stem fraction in Peruaçu vereda; H – deposition of the stem fraction in Almescla vereda; I – deposition of the debris fraction in Peruaçu vereda; J – deposition of the debris fraction in Almescla vereda. Different letters accompanying the means indicate statistical difference at a level of $p < 0.05$ according to the T-test.

Table 5. Macronutrients (measured in kg × km^2 × year^{-1}), returned through the litter leaf fraction in one year in the Peruaçu (degraded) and Almescla (preserved) veredas located in the Veredas do Peruaçu State Park and Environmental Protection Area of the River Pandeiros, Minas Gerais State, Brazil

Macronutrients	Peruaçu (degraded) vereda		Peruaçu (degraded) vereda		p-value
	Mean	SD	Mean	SD	
Ca	0.00691	0.00384	0.00522	0.00296	0.06
N	0.00400	0.00168	0.00307	0.00130	0.04
K	0.00108	0.00068	0.00106	0.00073	0.89
Mg	0.00038	0.00020	0.00047	0.00030	0.17
S	0.00028	0.00012	0.00022	0.00010	0.04
P	0.00014	0.00005	0.00011	0.00005	< 0.05

Note: SD – standard deviation.

Decomposition encompasses all physical and chemical processes that transform litter (Aerts 1997; Li et al., 2023), and it constitutes a key process for ecosystems (Szefer et al., 2017). In this context, decomposition is an important step for the cycling of carbon and nutrients, as well as their consequent return to the soil (Austin et al., 2014). The higher decomposition rate found in the conserved veredas may be related to better environmental conditions of these ecosystems, such as a milder temperature (Silva et al., 2018) and higher soil moisture (Silva et al., 2018; Brito et al., 2020), since it has denser vegetation and a larger basal area, while Peruaçu vereda has more open vegetation and a smaller basal area (Nunes et al., 2022), which provide higher microbial activity in the material on the ground.

We can observe a decrease in C-mic and an increase in qCO_2 in the degraded vereda, which may indicate stress on the microbial community (Anderson & Domsch, 1993, Araújo et al., 2017). High levels of qCO_2, as in Peruaçu vereda, may represent less sustainable microbial communities and faster mineralisation (Raiesi & Beheshti, 2015), leading to changes in the cycling of C and nutrients, and loss of C to the atmosphere (Chen et al., 2018). High C-mic values, as found in Almescla vereda, may indicate higher immobilisation of C and consequently lower losses of C to the atmosphere (Raiesi & Beheshti, 2015). The microorganisms present in the soil control several ecosystems functions, such as biogeochemical cycles, litter decomposition, and nutrient cycling (Onen et al., 2020). The soil microbial biomass is the most active part of the soil (Brito et al., 2020). Microbial biomass can be considered a good indicator of its quality, as it is the edaphic component most sensitive to disturbances (Zornoza et al., 2009) and presents the fastest responses to the physicochemical attributes (Araújo & Monteiro 2007). Our results indicate a better condition for the microbial community in the more conserved vereda. Regarding the SCS, similar to our results, Zelarayán et al. (2015) found 47% losses of SCS in the 0–20 cm layer in the riparian forest in the Amazon with a very high level of degradation. Wetlands, including veredas, are environments with a large storage capacity for C and are highly vulnerable (Wantzen et al., 2012), disturbances, like drying, change the anoxia conditions and consequently the microbial activity (Chen et al., 2018), triggering huge losses of C to the atmosphere (Wantzen et al., 2012).

The litter plays an important role in nutrient cycling and in maintaining soil fertility (Edwards et al., 2018; Silva et al., 2018). Previous studies in other phytophysiognomies of the Cerrado found litter deposition values similar to those obtained in the present study (e.g. Cianciaruso et al., 2006; Inkotte et al., 2019; Sales et al., 2020). The highest litter deposition was found in a degraded vereda. Similar to our results, Moraes & Prado (1998) suggested that pioneer species, which are established after disturbances, present higher litterfall production than species from primary forests. Such species, as *Astronium fraxinifolium* Schott (pioneer in deciduous and dry environments), *Bowdichia virgilioides* Kunth (deciduous and xerophyte), as well as *Xylopia emarginata* Mart. and *Cecropia pachystachya* Trécul, pioneer species (Batista et al., 2008) that presented high density in the study area, probably contributed to the increase in litterfall production in the Peruaçu vereda since the composition and structure of the forest can modify this process (Becker et al., 2015). Among litter fractions (leaf, stem, reproductive material, and debris), the leaf fraction had the highest amount in the intercepted litter. Previous studies indicated that leaf portion may represent around 70% of the litter in various Cerrado phytophysiognomies (Cianciaruso et al., 2006; Lopes et al., 2015).

Litter deposition may be a physiological response, influenced by seasonality, which can be observed in tropical forests, through the peaks of litter production in the dry season (Valenti et al., 2008; Zhang et al., 2014; Brasil et al., 2017; Souza et al., 2019; Sales et al., 2020), possibly being a response of vegetation to water deficit (Alvarenga et al., 2015). Also, the higher stem production in the Peruaçu vereda may be related to the lower dominance of the arboreal community in this area (Nunes et al., 2022). This occurrence may have been enhanced by the action of wind and rain (Almeida et al., 2015). Likewise, the higher production of reproductive material in the Almescla vereda in the rainy season may be related to less stressful conditions for the plants (Silva et al., 2018), as well as more favourable conditions for germination (Almeida et al., 2015) in addition to the adaptation of plant species to climatic seasonality (Silva et al., 2018). Given that Almescla vereda shows few signs of degradation, it is considered a preserved vereda in this study.

Previous studies (Cianciaruso et al., 2006; White et al., 2013; Silva et al., 2018; Li et al., 2023) found similar results to those obtained in this study regarding decomposition rates. Additionally, Brito et al. (2020) investigated decomposition in veredas using another methodology, which may influence the differences observed in the results. White et al. (2013) found that the availability of nutrients for plants is faster when the half-life of litter is shorter, which happens in Almescla vereda when compared to Peruaçu vereda. The number of nutrients returned by litter can vary due to factors such as vegetation type, climatic conditions, and locations (Qiu et al., 2002). Likewise, the concentration of nutrients in litter may also be a response to soil fertility (Vitousek & Sanford, 1986), like the amount of P, which was higher in Peruaçu vereda in both litter and soil, or may be related to translocation or retention of each nutrient in the plant before organ senescence. For example, Ca is a structural element (Hawkesford et al., 2012) and has a low internal translocation rate (Schumacher et al., 2004). Therefore, it is presented in higher concentrations in senescent tissues. P has high mobility in plant tissues (Schumacher et al., 2004), which makes the concentration of this element higher in new and developing tissues and lower in senescent plant tissues (Hawkesford et al., 2012).

Conclusions

From this study, we can conclude that degradation in veredas leads to irreversible damage in Brazilian Cerrado. To the best of our knowledge, this is the first study evaluating the impacts of drying on soil attributes and nutrient cycling in veredas. The drying of the veredas disrupts the microbiological community, increasing metabolic activity and organic matter consumption, resulting in soil nutrient depletion and scarcity for plant growth. Changes in soil quality prevent species adapted to veredas from thriving, leading to colonisation by invasive species with different composition and litter deposition patterns. These events can impact litter decomposition, altering nutrient cycling and soil quality, thus affecting ecological functions within the veredas. This results in a reduction in carbon stock and its immobilisation in the soil, contributing to climate change on a global scale. In light of these findings, it is imperative to implement comprehensive conservation strategies for veredas in the Brazilian Cerrado, emphasising the preservation of soil attributes and litter deposition dynamics.

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КРУГОВОРОТ ПИТАТЕЛЬНЫХ ВЕЩЕСТВ И КАЧЕСТВО ПОЧВЫ В НАХОДЯЩИХСЯ ПОД УГРОЗОЙ ИСЧЕЗНОВЕНИЯ ПАЛЬМОВЫХ БОЛОТАХ НА ДВУХ ООПТ СЕРРАДО БРАЗИЛИИ

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Пальмовые болота (veredas) – это увлажненные местообитания, имеющие большое значение для бразильского Серрадо. Понимание качества почвы и экологических процессов, протекающих между почвой и растительностью пальмовых болот, может дать представление о динамике экосистемы. Целью данного исследования было оценить накопление и разложение подстилки, а также качества почвы, включая химические, физические и микробиологические характеристики, в двух находящихся под угрозой исчезновения пальмовых болотах Бразилии, имеющих разную степень нарушенности среды обитания. Исследование проводилось в Альмескле (сохранившееся пальмовое болото) на территории заповедника реки Пандейрос и в Перуасу (нарушенное пальмовое болото), расположенном в государственном парке Вередас-ду-Перуасу. Накопление подстилки измеряли с помощью коллекторов 50 × 50 см из нейлоновой сетки толщиной 1 мм, а разложение оценивали с использованием мешков для мусора. Гранулометрию почвы, содержание углерода и питательных веществ, биомассу микроорганизмов почвы оценивали на глубине 20 см. Накопление подстилки было выше в Перуасу: на долю листовой фракции приходилось более 70% от общего количества на обоих участках исследования. Константа разложения (kc) была выше на пальмовом болоте Альмескла. На обоих изученных пальмовых болотах концентрации питательных веществ уменьшалась в следующем порядке: Ca > N > K > Mg > S > P. На пальмовом болоте Перуасу наблюдалось более высокое содержание глины, доступного фосфора и кальция. Микробный углерод, общий органический углерод, микробный коэффициент и запас углерода были выше на пальмовом болоте Альмескла, тогда как метаболический коэффициент был выше на пальмовом болоте Перуасу. Полученные результаты показывают, что деградация экосистем пальмовых болот может привести к изменениям в круговороте питательных веществ с уменьшением отложения подстилки и снижением запасов углерода.

Ключевые слова: возврат питательных веществ, накопление подстилки, плодородие почвы, почвенные микроорганизмы, разложение подстилки, сток углерода