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EFFECTS OF *Eucalyptus* PLANTATIONS ON THE PHYSICAL AND CHEMICAL PROPERTIES OF SOIL IN FLOODPLAINS OF THE EASTERN REGION OF PARAGUAY

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ABSTRACT

The floodplains of the eastern region of Paraguay have soils with a shallow water table that causes flooding in months of heavy rainfall (August to December). The soils, predominantly Ultisols with gleyic properties, display high contents of soil organic matter (SOM) and an acidic pH. These environments are being transformed into *Eucalyptus camaldulensis* Dehnh. plantations, primarily for energy purposes. The aim of this study was to evaluate the chemical and physical properties of soils in eucalyptus plantations established on the native lowland grasslands. For this purpose, three chronosequences were selected, consisting of native grasslands and eucalyptus plantations aged between 2 and 8 years. In each system, the chemical and physical properties were determined at depth increments (0–5, 5–10, 10–20, and 20–40 cm). Each soil sample in the plots included six repetitions for both chemical and physical analyses. In the first years of eucalyptus planting, soil organic carbon (SOC) decreased by 50 % due to the intensive tillage carried out in the first years to establish the eucalyptus plantations. SOC concentrations recovered over time, although they did not reach the levels observed in the native grasslands. Soils with eucalyptus plantations displayed a higher bulk density (up to 1.35 g cm^{-3}), greater acidity (pH value of 4), and a decrease in phosphorous (P) and exchangeable bases (up to 30 %) in comparison with natural grasslands. It is concluded that, in order to prevent the degradation of the chemical and physical properties of the soil in natural grasslands, it is necessary to plan practices that include land-use changes with native forest species and reconsider the practice of transforming these natural systems.

Keywords: *Andropogon lateralis* Nees, *Paspalum notatum* Flüggé, hydromorphic soils, forestry, drainage.

INTRODUCTION

On a global scale, floodplains characteristically display soils with high carbon (C) and store approximately 12 % of the worldwide reserves (Hussain *et al.*, 2020; Keller *et al.*,

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2021). In addition, they play a relevant part in biodiversity and the regulation of the water cycle and greenhouse gases (Sutfin *et al.*, 2016). A total of 40 % of the eastern region of Paraguay is covered by lowlands found in the Humid Chaco ecoregion (Ávila-Torres *et al*., 2018). This landscape is represented by wide prairies covered in natural grasslands, dominated by *Andropogon lateralis* Nees and *Paspalum notatum* Flüggé, and is used for extensive cattle farming. These environments are affected by floods from the Paraguay and Paraná rivers, which are known for their extensive biodiversity and enormous environmental benefits, such as C reserves in soils or water flow regulation.

Soil organic material (SOM) reserves in the floodplains are greater than in forest or agricultural soils of the highlands of the same regions (Encina-Rojas *et al.*, 2023). The organic C reserves are determined by the contribution of organic remains derived from the high density and number of roots, which is typical of the natural grasslands of this type of ecosystem (Tonucci *et al.*, 2017). These properties are similar to the prairies in the floodplains of the Paraná River, near the province of Corrientes, Argentina (Navarro and Kurtz, 2019).

Native grasslands are currently being transformed into eucalyptus plantations, which implies an intensive intervention of the soil, altering some ecosystem functions such as the water cycle and the recycling of nutrients (González-Sosa *et al.*, 2024). There are studies that show that the degradation of these natural grasslands could contribute to altering the hydrology and mineralization of the large SOM reserves, increasing the emission of greenhouse gases and reducing biodiversity (Habel *et al.*, 2013; Keller *et al.*, 2021). Studies on South American grasslands indicate that eucalyptus causes reductions in water levels and the net flow of underground waters (Christina *et al.*, 2017). Vic *et al.* (2005) evaluated the water cycle in the Argentinean pampas before and after forestation and found the eucalyptus reduced the water level during dry periods due to the high evapotranspiration.

Eucalyptus spp. are the forest species that have integrated most efficiently in tropical climates. Due to their speedy growth, they extract important nutrients in short growth cycles (Santana *et al.*, 2008; Pulito *et al.*, 2015; Rocha *et al.*, 2019). Studies carried out by Laclau *et al.* (2010) in native grasslands in Brazil showed that Ca, Mg, and K concentrations in the soil decreased with the establishment of eucalyptus, generating acidity and altering the dynamics and availability of phosphorous (Boulmane *et al.*, 2017).

In floodplains with native grasslands in Paraguay, eucalyptus plantations are swiftly growing. Therefore, the aim of this investigation was to evaluate the medium- and long-term impacts of these plantations on the chemical and physical properties of the soil. This data will help determine the impacts of the eucalyptus plantations on these ecosystems to develop sustainable management strategies for landscape planning and to propose practices to preserve soil properties.

METHODOLOGY

Location and characteristics of the area of study

The investigation was carried out in the eastern region of Paraguay, located in a floodplain of the Tebicuary River, an affluent of the Paraguay River. The study area is located in three districts of the Department of Caaguazú: Coronel Oviedo, San José, and RI 3 Corrales (Figure 1), in the Atlantic Forest of the Alto Paraná ecoregion and the Selva Central in the Upper Paraná basin (Ávila-Torres *et al.,* 2018). The region has a subtropical climate (Köppen's classification) with a mean annual rainfall of 1700 mm, a mean annual temperature of 26 °C, and an average altitude of 200 m.

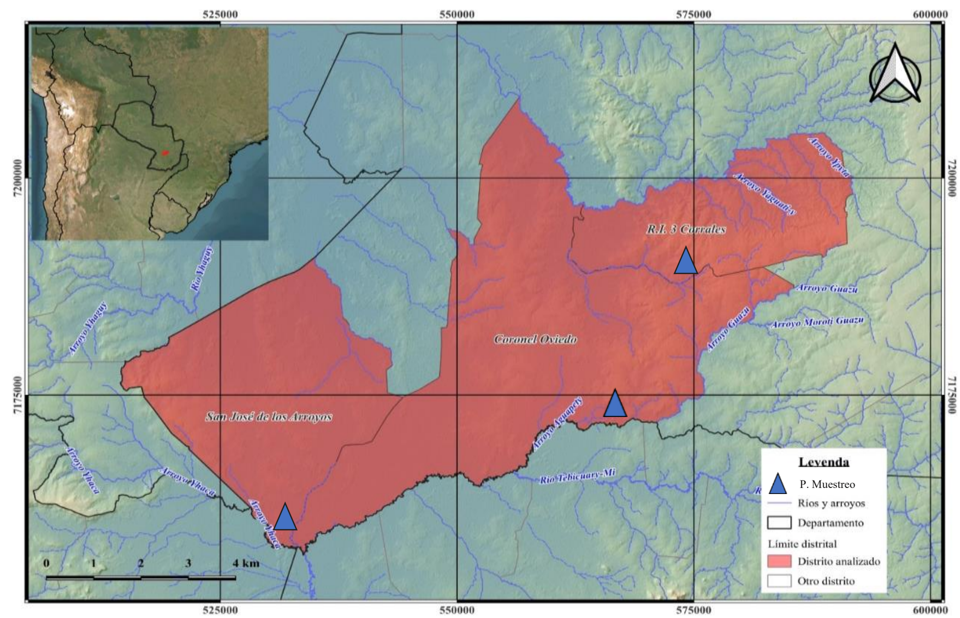

Figure 1. Location of the evaluated plots in the Department of Caaguazú, eastern Paraguay.

Eucalyptus establishment in floodplains

The main purpose of eucalyptus plantations is to generate biomass for energy and paper production. Establishing eucalyptus plantations in these lowlands generally requires intensive tillage, typically using a moldboard plow and subsoiler to improve rooting and accelerate drainage during months of high rainfall. The forest species used was cloned *Eucalyptus camaldulensis* Dehnh., which is planted at a density of 625 plants ha^{-1} (4 m between rows and 4 m between plants). During the planting process, a single base fertilization is used with 60 kg ha^{-1} of phosphorous oxide (P_2O_5) using triple superphosphate. Eucalyptus grows 3 to 5 m in height in its first year, reaching 20 m by the age of 8 years.

Experimental design and sampling

In the selected plots, eucalyptus plantation systems of varying ages (2 to 8 years) were identified on the same natural grassland that served as a reference control (Table 1). The plantations covered surfaces between 50 and 350 ha. In the adjacent areas to the plantations, natural grasslands were found. The sample units were the natural grasslands and the eucalyptus plantations established as chrono-sequences: a- (Coronel Oviedo): 2, 4, 6, and 8 years, b- (San José): 4, 6, and 8 years, and c- (RI 3 Corrales): 8 years.

Table 1. Evaluated native grassland and eucalyptus plantation (*Eucalyptus camaldulensis* Dehnh.) plots evaluated on the Tebicuary River floodplains in eastern Paraguay.

Location	Plot #	Years of plantation
Coronel Oviedo	NG	
	E2	2
	E4	4
	E6	6
	E8	8
San José	NG	
	E4	4
	E6	6
	E8	8
RI 3 Corrales	NG	
	E8	8

NG: natural grassland; E: eucalyptus (2, 4, 6, or 8 years of growth).

In the central zone of each plot, both in the grasslands and the eucalyptus plantations, sampling points were selected. Pits were opened, and samples were taken from depths of 0–5, 5–10, 10–20, and 20–40 cm. Six independent samples were extracted, made up of 12 samples each, for chemical analyses and the measurement of apparent density. Soil samples were stored in plastic bags, labeled, and taken to the laboratory, where they were dried in the open, sieved at 2 mm, and homogenized before chemical analysis.

Analysis of the soil properties

The pH was measured using H_2O and $CaCl_2$ 0.01 M in a 1:2 soil-solution ratio. The C content was determined through humid combustion (Walkley and Black method). The exchangeable Al was extracted with KCl 1 M, and the total N (Nt) was extracted with the Kjeldahl method. The carbon-nitrogen ratio (C/N) was also calculated. The exchangeable Ca, K, and Mg were obtained using ammonium acetate (1 M, pH 7) and determined by atomic absorption spectrophotometry (AAS). Available Fe, Cu, Mn, and Zn were extracted with Mehlich solution and determined by AAS. Extractable P was measured using the molybdenum blue method, and soluble B in hot water was determined with the azomethine-H method. The distribution of the particle size (clay <2 μm, lime from 2 to 50 μm, and sand >50 mm) in a single layer (0–5 cm) was also determined. The apparent density was calculated from the weight of the soil at 100 °C and the volume of the sampling cylinder.

Statistical analyses

Average values, standard deviations, and variation coefficients were determined for each variable, and the data were subsequently analyzed using an analysis of variance (ANOVA). The means of the treatments were compared using Tukey's test, and Pearson's correlation was also carried out. For the Principal Components Analysis (PCA), Bartlett's test was first carried out, and once it became significant, the PCA was performed between the natural grassland and the eucalyptus plantation ages using the SAS statistical package (2009).

RESULTS AND DISCUSSION

Soil organic carbon, total nitrogen, and C/N ratio

The soils displayed soil organic carbon (SOC) concentrations between 2 and 3.6 % in plots repopulated with *E. camaldulensis*. These values were reduced substantially in comparison with the natural grasslands (Table 2). After the soil was prepared, SOC concentrations decreased by approximately 50 % until the depth of approximately 40 cm (Table 2, Figure 2). Ramos-Hernández and Martínez-Sánchez (2020) evaluated the C capture of native grasslands in southeastern Mexico, where they found that the *Paspalum* spp. species provide larger amounts of C in comparison to other grass species. Viglizzo *et al.* (2019) mention that the grasses in lower areas of South America capture large amounts of C in comparison to other species and that this could be compensating for greenhouse gas emissions from livestock production.

Total nitrogen (Nt) concentrations (Table 2) followed the same tendency as C, with a correlation (Table 3) of 0.99 ($p < 0.001$). However, unlike C, Nt showed no recovery through the years in eucalyptus plantations. The C/N ratio in natural grasslands was 9:14 (Table 2), whereas in all eucalyptus plantations, the ratio increased significantly (greater than 20), despite the lower Nt concentrations.

This study shows that the important C reserves accumulated in the native grasslands decrease with the establishment of intensive eucalyptus plantations. In the first years, the C reserves dwindle by up to 50 %. Another effect recorded was the Nt loss and the subsequent increase of the C:N ratio, which went from 10–12 in the grasslands to 19–25 in the plantations. Despite the effect being partly due to tilling, which dilutes the contents of organic C and N in the surface layer of the soil, it is also feasible that the drainage implemented significantly reduced the level of the water table and,

Table 2. Chemical and physical soil properties in the 0–5 cm-deep layer of natural grasslands and eucalyptus plantations (*Eucalyptus camaldulensis* Dehnh.) in plots evaluated on the Tebicuary River floodplains in eastern Paraguay.

District	Plot	pH		C	Nt	C/N	P	ECEC	Al	K	Ca	Mg	Ad	S	L	Cl
		$CaCl_2$	H_2O	%			mg kg^{-1}	cmol$_c$ kg^{-1}					g cm^{-3}	%		
Coronel Oviedo	NG	4.6a	5.1a	2a	0.2 a	9b	6.0a	7.3 a	0.1c	0.1a	1.29a	0.44a	0.98a	75a	5a	20a
	E2	4.3b	4.6b	1.2c	0.08 a	15a	3.2b	5.9b	1.2b	0.02c	0.85b	0.26c	1.21b	74a	5a	21a
	E4	4.2b	4.6b	1.4b	0.10 a	14a	2.5b	6.4b	1.4a	0.04c	0.96b	0.35c	1.22b	79a	4a	17a
	E6	3.9c	4.3c	1.5b	0.11 a	14a	3.5b	6.5b	1.6a	0.02c	0.98b	0.38b	1.23b	79a	3a	18a
	E8	3.9c	4.3c	1.6b	0.11 a	15a	3.4b	5.9b	0.1c	0.08b	1.00b	0.41b	1.29b	82a	2a	16a
	p-value	0.001		0.001	0.001	0.001	0.001	0.001	0.001	0.01	0.01	0.001	0.01	ns	ns	ns
San José	NG	4.3a	4.8a	2.8a	0.19 a	15b	6.28a	8.3a	1.0b	0.09a	0.99a	0.06b	0.89a	74a	5a	21a
	E2	3.7b	4.4b	1.9b	0.09 b	21a	3.05b	7.1b	1.2a	0.02b	0.52c	0.03b	1.19b	79a	4a	17a
	E4	3.9b	4.3b	2.3b	0.11 a	21a	4.30b	7.2b	1.3a	0.06b	0.76c	0.1b	1.21b	78a	5a	17a
	E6	3.9b	4.1b	2.2b	0.12 a	20a	2.91b	7.6b	1.2a	0.06b	0.85b	0.15a	1.23b	78a	5a	17a
	p-value	0.001		0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.01	0.01	0.001	ns	ns	ns
RI 3 Corrales	NG	4.0a	4.4a	3.6a	0.25 a	14b	4.62a	7.6b	1.2b	0.12a	1.00a	0.14b	0.92b	73a	5a	22a
	E8	3.8b	4b	3.0b	0.10 a	30a	3.13b	6.7a	1.9a	0.07b	0.87b	0.25a	1.33a	75a	4a	21a
	p-value	0.001		0.001	ns	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	ns	ns	ns

Nt: total nitrogen; ECEC: effective cation exchange capacity; Ad: apparent bulk density; S: sand; L: lime; Cl: clay; NG: natural grassland; E: eucalyptus (2, 4, 6, or 8 years of growth); ns: not significant. Different letters indicate significant differences ($p \leq 0.05$).

consequently, improved soil aeration, leading to an increase in the mineralization of organic material (Pérez-Cruzado *et al.,* 2012; Poeplau *et al.,* 2011).

The reduction of soil organic matter (SOM) in these lowland soils is due in great part to the intensive preparation of the soil for the establishment of eucalyptus. This practice involves the removal and mixing of horizons, reducing the SOM content on the surface. Studies mention that soil scarification reduces SOM by nearly 50 % (Jiménez-Esquilin *et al.,* 2008), and this loss increases with the use of subsoiling and moldboard plowing, which promote erosion and the leaching of organic compounds and nutrients from the soil (Walmsley and Godbold, 2010). Eucalyptus plantations, when combined with other grassland systems to create silvopastoral systems, may improve the concentrations of SOM in the soil profile (Boulmane *et al.,* 2017), although the final evolution of SOM is highly determined by the initial content of the soil (Cook *et al.,* 2016).

The loss of Nt, with the subsequent increase of the C:N ratio, can be attributed to denitrification and even to the leaching of mineral N, which may affect water. This increase in the C:N ratio, along with the strong acidity, may lead to lower N availability for the plants (Pulito *et al.,* 2015). In this regard, some studies have found high C:N ratios in the soil under eucalyptus plantations in comparison to native plant

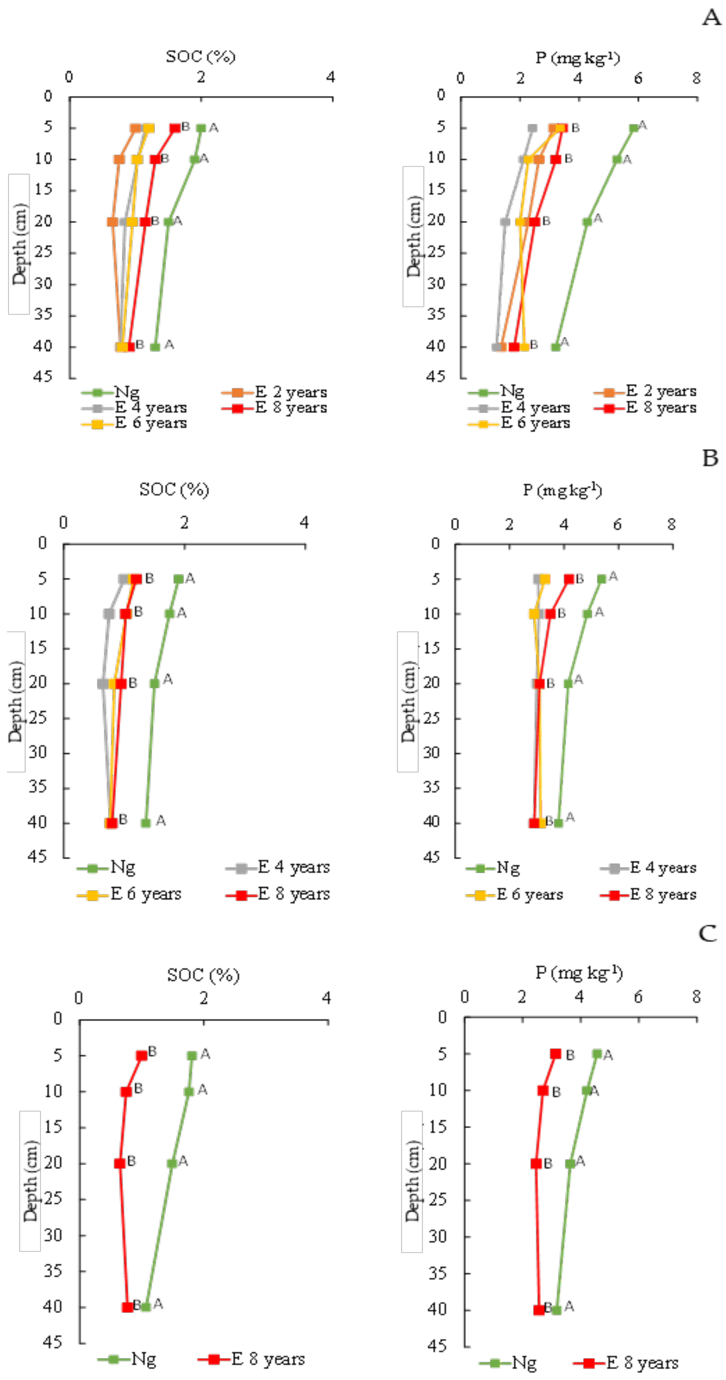

Figure 2. Soil organic carbon (SOC) concentration and available P at different depths, by district, in the natural grasslands and eucalyptus plantation (*Eucalyptus camaldulensis* Dehnh.) plots evaluated on the Tebicuary River floodplains in eastern Paraguay. Different letters indicate significant differences ($p \leq 0.05$).

Table 3. Correlation coefficients between fertility parameters of the natural grasslands and eucalyptus plantations (*Eucalyptus camaldulensis* Dehnh.) in plots evaluated on the Tebicuary River floodplains in eastern Paraguay.

Variable	pH	Al	SOC	Nt	C/N	P	ECEC	K	Ca	Mg	Ad
pH	1										
Al	-0.89	1									
SOC	----	----	1								
Nt	----	----	0.99	1							
C/N	----	0.62	0.33	----	1						
P	-0.82	-0.84	0.79	----	----	1					
ECEC	0.73	----	0.69	----	----	0.75	1				
K	0.75	-0.53	----	----	----	----	----	1			
Ca	0.76	-0.84	----	----	----	0.63	----	0.62	1		
Mg	0.82	-0.87	----	----	----	----	----	----	0.78	1	
Ad	-----	----	-0.80	----	----	----	----	----	----	-----	1

SOC: soil organic carbon; Nt: total nitrogen; ECEC: effective cation exchange capacity; Ad: apparent bulk density.

soil, as well as a lower microbial activity (Lima *et al.,* 2006). This effect is limiting for eucalyptus crops due to a lower availability of N during its cycle and for subsequent plantations (Pulito *et al.,* 2015).

Among the fast-growing forest species, eucalyptus is characterized by a low density of leaves, and as a consequence, lower amounts of organic material are deposited on the surface of the soil (Hemes *et al.,* 2018). Eucalyptus plantations present less C in comparison with natural systems due to the lower contribution of organic compounds and the slow decomposition of biomass (Paul *et al.*, 2002), as well as the lower amount of moisture found in the soil. Studies indicate that foresting with eucalyptus can maintain SOM content (Pulrolnik *et al.,* 2009); however, other studies indicate that these plantations reduce the reserves of SOM in the soil profile due to a lower biomass contribution, providing plant residues with high concentrations of lignin (Hemes *et al.,* 2018).

Apparent bulk density of the soil and texture

In this study, results indicate a greater apparent bulk density in the new eucalyptus plantations (greater than 1.3 g cm^{-3}), in comparison to natural grasses (0.98 g cm^{-3}). The results of the apparent density present a negative correlation (-0.80, $p < 0.01$) with SOC (Table 3); that is, as SOC decreases, soil density increases. The results display high contents of sand (80 %), lime (5 %), and clay (15 %), and no variations with the establishment of the eucalyptus trees. The loss of SOC in the eucalyptus plots results in the increase of apparent soil density, reduction of porosity and water infiltration, and increase in the surface runoff. The loss of SOC leads to increased soil density and may result in a decrease in root growth, lower SOM fixation, water infiltration, and a reduction in the biological activity of microorganisms (Conte *et al.*, 2011).

Extractable phosphorus

Natural grasslands displayed extractable P concentrations ranging from 2 to 8 mg kg^{-1}, which can be attributed to the natural acidity of these soils. P concentrations fell significantly with the establishment of the eucalyptus plantations, with losses of approximately 30 % at the time of the establishment, and recovered without reaching the original levels at the end of the rotation. In all chronosequences studied (Table 2, Figure 2), P concentrations were lower in the eucalyptus plantation systems, ranging between 2 and 3 mg kg^{-1}. The concentration of available P correlates negatively (Table 3) with acidity ($r = -0.82$, $p < 0.001$); that is, as acidity increases with eucalyptus plantations, P availability decreases. Likewise, P presented a high correlation (Table 3) with SOM ($r = 0.79$, $p < 0.001$). The transformation of natural grasslands to plantation systems generated losses in the reserves of available P at all depths studied (Figure 2) in the first years of planting and up to 8 years without recovering its natural concentration.

Some nutrients, such as P, decrease their availability with the acidity of the soil. Around 80 % of the P in the surface of the soil is considered to be found in its organic form, which is why, when SOM concentrations are reduced, the P extractable is reduced. Pulrolnik *et al.* (2009) and Hemes *et al.* (2018) mention that the biomass of the eucalyptus presents high amounts of polysaccharides and lignin, which hinder its decomposition and the accumulation of SOM, affecting the reserves of P and Nt.

Fast-growing and intensively managed forest species, such as eucalyptus plantations, have high needs for P and are efficient in its absorption and translocation in the plant (Fife *et al.*, 2008). In Brazil, P availability in Oxisols was evaluated in eucalyptus plantations, finding a low availability compared to the natural grasslands (Foltran *et al.*, 2019). Nutrient reduction in eucalyptus plantation soils was reported by several authors (Gonçalves *et al.*, 2020; Rocha *et al.*, 2019), which is why the use of fertilizers and agricultural lime is important to increase the availability of nutrients and the productivity of the plantation systems.

pH, Al, effective cation exchange capacity, and exchangeable nutrients

Natural grasslands displayed a potentially acidic pH (4.8), and the plantation of eucalyptus increased the acidity; at the same time, exchangeable Al increased ($r = -0.89$) in the studied chronosequences (Tables 2 and 3), particularly at the end of the rotation at 8 years. The relation between pH and Ca, Mg, and K presented a high negative correlation (Table 2), indicating that as the acidity increased, the concentration and availability of the studied bases decreased.

In the new eucalyptus plantations, a reduction was observed in the concentrations of exchangeable Ca, Mg, and K (Table 2, Figure 3), as well as a reduction in these when the sampling depth increased up to 40 cm. The effective cation exchange capacity (ECEC)

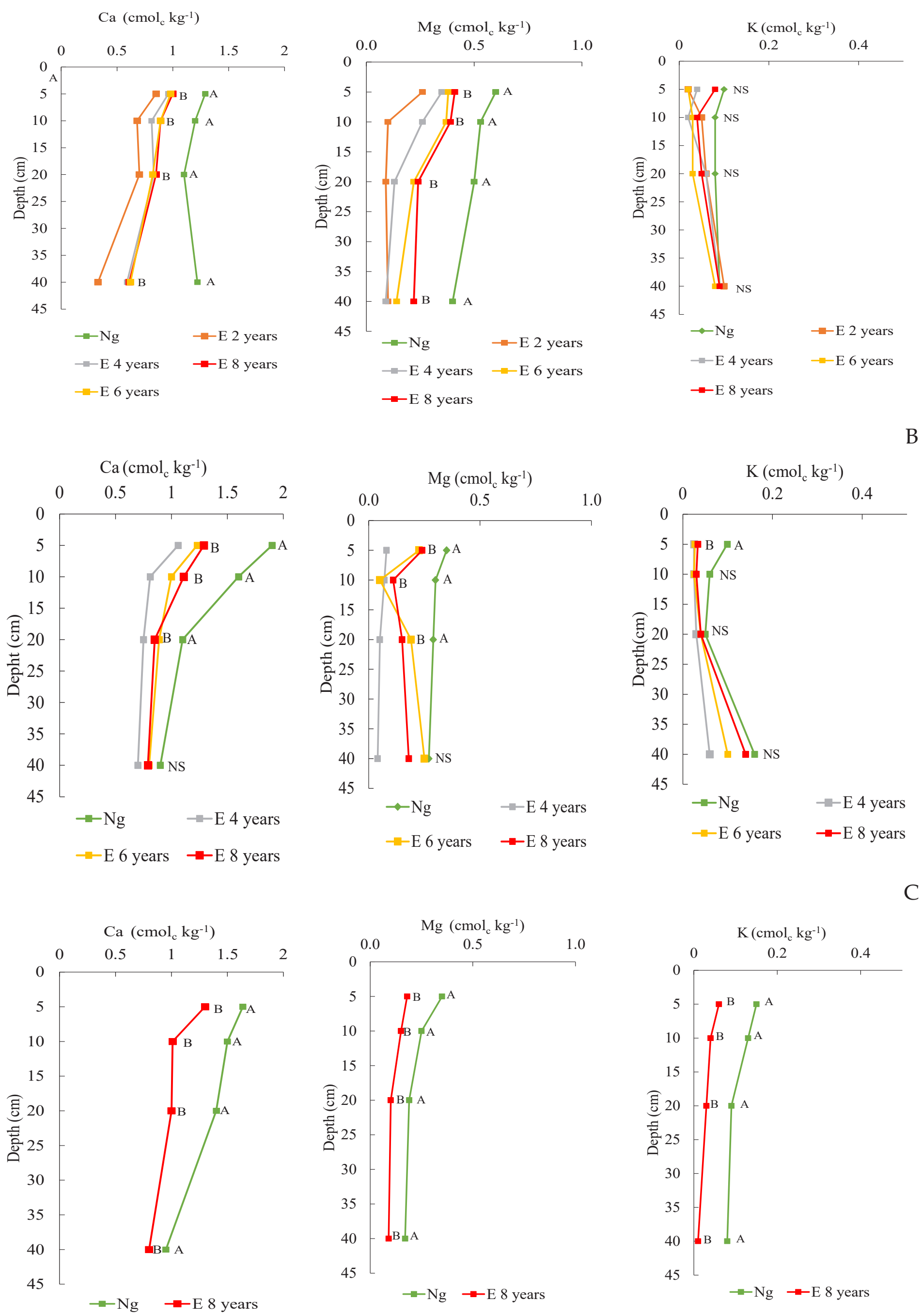

Figure 3. Concentrations of exchange calcium (Ca), magnesium (Mg), and potassium (K) at different soil depths in plots evaluated on the Tebicuary River floodplains in eastern Paraguay. Different letters indicate significant differences ($p \leq 0.05$).

was low (7.5 $cmol_c$ kg^{-1}) in the natural grasslands and decreased in all treatments with eucalyptus.

Studies mention a strong increase in the acidity of the soil has a direct impact on the availability of nutrients and leads to the appearance of toxic elements such as Al (Holland *et al.*, 2017), which is an element that limits the growth of all plant species since it is not an essential element. The evolution of the quality of soils under eucalyptus plantations was evaluated by Rocha *et al.* (2016; 2019), finding a high acidity in the soil and a very low availability of exchangeable bases (Merino *et al.*, 2005; Villalba-Martínez *et al.*, 2022).

Ca absorption is proportional to stem growth and biomass during the cycle of the eucalyptus, while the Mg requirement is greater in the first years (Laclau *et al.*, 2010; Rocha *et al.*, 2016). In successive plantations, K deficiencies reduce the stomatal opening (Laclau *et al.*, 2010), and the abscission of leaves becomes the main strategy for transpiration in moments of water scarcity, which is why one of the consequences of K deficiency in eucalyptus is the loss of leaves. Eucalyptus absorbs large amounts of Ca, Mg, and K at different depths. This extraction is correlated with the growth rate (Cook *et al.*, 2016; Rocha *et al.*, 2016). Consequently, successive eucalyptus plantations lead to reductions in the reserves at critical levels in the soil (Boulmane *et al.*, 2017).

Principal components analysis

The principal components analysis (PCA) corresponding to the three studied chronosequences (Figure 4) shows the distance marked between the natural grasses

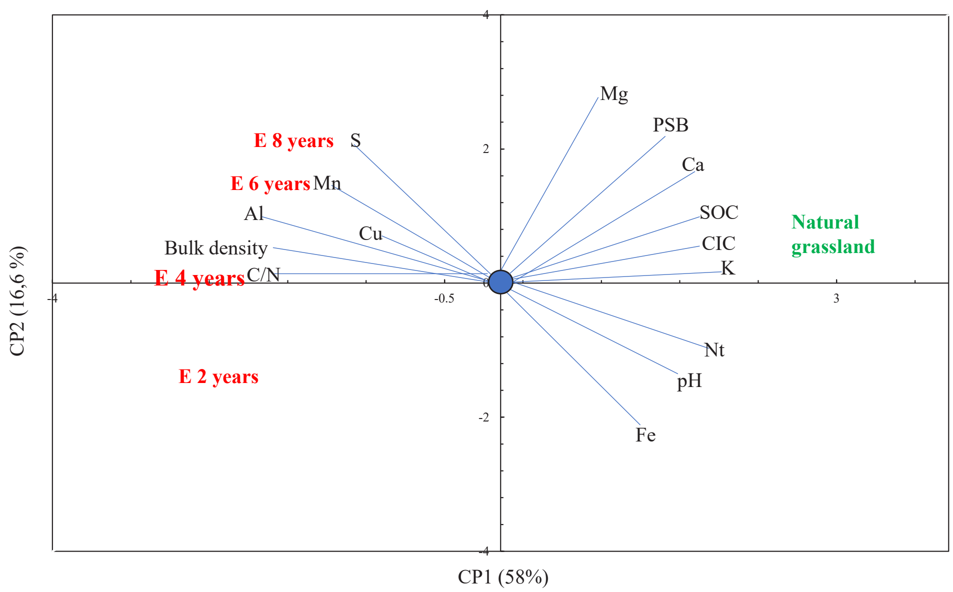

Figure 4. Principal component (CP) analysis of the evaluated natural grasslands and eucalyptus plantations (*Eucalyptus camaldulensis* Dehnh.) in plots evaluated on the Tebicuary River floodplains in eastern Paraguay.

and the eucalyptus plantations. In the plots studied, the natural grassland systems were characterized by a high accumulation of C and available nutrients, whereas the systems with eucalyptus plantations were characterized by the accumulation of Al, an increase in density, and the loss of nutrients.

Just as other intensive cropping systems, eucalyptus plantations require important amounts of nutrients, mainly N, P, K, and Ca. Santana *et al.* (2008) found that the aerial biomass of eucalyptus in southern Brazil contained, in kg ha^{-1}, 483 of N, 37 of P, 301 of K, and 620 of Ca at a standard harvest age of 6.5 years. The highest accumulation of Ca in these plantations was observed in the wood of the trunk, in comparison with the leaves and branches (Leite *et al.,* 2011; Santana *et al.,* 2008). It is therefore highly unlikely that the restitution of nutrients can take place through the contribution of eucalyptus biomass.

CONCLUSIONS

The establishment of eucalyptus plantations on the natural grasslands, which implies tilling and drainage, reduced soil organic carbon (SOC) concentrations. Throughout the 8 years of rotation, a recovery was observed in the SOC reserves, but it was not enough at the end of the cycle to counteract the loss. In the same period, the N and P reserves presented reductions of 50 %, related to the loss of SOC. Acidity was also produced, along with losses of up to 30 % of Ca, Mg, and K. Part of the losses were attributed to the intense nutrient extraction, which is characteristic of intensive eucalyptus plantations. The reduction of extractable P from the soil is due to the greater acidity that affects the mobility of this element, as well as the loss of SOM, which regulates the reserves of organic P in the soil. With the introduction of eucalyptus plantations, a greater apparent bulk density was observed in the soil in comparison with the native grasslands.

Based on the data presented, it is concluded that planning for these new systems is necessary, taking into account land management and soil conservation practices (tillage, fertilization, forestry management) to prevent fragile soils from being degraded and their fertility deteriorated, affecting their quality for future uses.

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