SILVOPASTORAL SYSTEMS ENHANCE SOIL QUALITY IN GRASSLANDS OF COLOMBIA

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ABSTRACT

In the tropical drylands of Colombia the soils subjected to traditional systems of livestock production are severely degraded and depleted of plant nutrients. Multistrata silvopastoral systems are viable alternatives to improve livestock production; however, it is unknown whether these systems can reduce the negative environmental impacts of traditional systems on soil quality. The objective of this study was to evaluate the effects of 13-year-old multistrata silvopastoral systems on soil quality parameters in degraded soils of the Sinu River valley, Colombia. The results show that the trees in the silvopastoral systems increased or maintained soil pH values and nutrient availability (phosphorus, potassium and calcium) with respect to the pastures with only grasses. The effects were significantly controlled by the types of plant species, particularly *Guazuma ulmifolia* and *Cassia grandis*.

Keywords: soil fertility, nutrient cycling, phosphorus, soil enhancement

INTRODUCTION

Soil degradation is one of the major constraints in the tropics affecting 500 million ha [1], threatening ecosystem services and food security for people in developing countries [2]. The Caribbean region of Colombia is an unfortunately example of this situation because 80-100% of the grasslands exhibit soil erosion, soil compaction, and low soil nutrient availability for livestock systems [3, 4, 5, 6]. The major cause is overgrazing and lack of proper management practices such as: monoculture of gramineae vs. plant diversity, adequate fertilization, soil conservation practices, and reduced tillage [7, 8, 9, 10]. Consequently, over time these soils exhibit high level of compaction (2.2-4.2 MPa) and low levels of plant nutrients (e.g., phosphate: <10 mg kg^{-1} and potassium: <0.11 $cmol_c$ kg^{-1}) that diminishes forage quality and availability, particularly in the long dry season [4, 6]. As a result of that, there is low animal carrying capacity (one animal per ha), low weight gain (< 300 g day^{-1}), late age for slaughter (30-36 months), and high cost of production (US\$0.80 kg^{-1}) [6, 8].

As an alternative, silvopastoral systems can be successfully implemented because they can provide several benefits: animal comfort and productivity, litter supply, nutrient cycling, water infiltration, soil bulk density, soil fauna, and biodiversity [11, 12, 13, 14, 15, 16]. Unfortunately, in the tropics there are not sufficient data to support these claims on soil quality parameters [17, 18, 19] as it occurs in the temperate zone [20, 21, 22], which limits the widespread use of this strategy [23, 24, 25].

Our hypothesis in this study was that soil quality parameters (e.g., soil pH, soil organic matter, plant nutrient availability) may be enhanced by silvopastoral arrangements in comparison with a pasture of gramineae monoculture; however, the magnitude of this effect may depend of the tree species considered in the arrangement. Thus, the aim was to evaluate the effect of 13-year-old multistrata silvopastoral arrangements on soil quality parameters.

MATERIALS AND METHODS

Site

This study was conducted in the experimental station of CORPOICA-Turipaná at Cereté, Córdoba, Colombia (8°51’ N, 75°49’ W, altitude 18 m a.s.l.). This region has two contrasting seasons: a rainy period from May to November and a dry period from December to April. The annual precipitation is 1380 mm, the mean temperature 28 °C, the air humidity is 81%, and a potential evapotranspiration of 1240 mm per year. According to Holdridge [26] the ecological life-zone is tropical dry forest.

Silvopastoral systems

For this study we used the plots established by Cajas-Girón [8] in 1998 (Table 1). The selection of plant species in the multistrata systems was designed according to the relative frequency in the region, the potential utility for livestock feed, and the acceptance of farmers, a critical factor to adopt these systems [27, 28]. The experimental design was a completely randomized block design (blocking according to the natural soil drainage), in each block there were three different silvopastoral arrangements and a control pasture composed of only grasses (*Dichanthium aristatum* and *Panicum maximum*; A0) that represents the traditional livestock production system in the region; the other systems besides grasses included three types of trees (*Guazuma ulmifolia, Cassia grandis, Albizia saman*; A1), trees and two shrubs (*G. ulmifolia, C. grandis, A. saman, Crescentia cujete, Leucaena leucocephala;* A2), and trees, shrubs, and two timber trees (*G. ulmifolia, C. grandis, A. saman, C. cujete, L. leucocephala, Pachira quinata,* and *Swietenia macrophylla;* A3) (Table 1). The livestock feed directly on grasses and shrubs (*C. cujete* and *L. leucocephala*). Each experimental plot had a size of 100 x 200 m (2 ha) and three replicates (total 12 plots, 24 ha).

Table 1. Multistrata silvopastoral systems evaluated in the Sinu River Valley, Colombia.

System	Composition	Plant species	Distance (m)*	No. of trees per ha	Tree height (m)	DBH (cm)**
A0	Pasture	*D. aristatum*	-	-	-	-
		P. maximum	-	-	-	-
A1	Pasture and trees	*D. aristatum*	-	-	-	-
		P. maximum	-	-	-	-
		G. ulmifolia	16x16	11	12.2±1.1	42.4±6.7
		C. grandis		11	13.3±0.5	36.3±2.2
		A. saman		11	19.2+2.0	68.0±2.9
				33		
A2	Pasture, trees, and shrubs	*D. aristatum*	-	-	-	-
		P. maximum	-	-	-	-
		G. ulmifolia	16x16 for trees	11	12.8±1.1	54.7±6.7
		C. grandis		11	14.0±0.5	38.6±2.2
		A. saman		11	21.4±2.0	67.3±2.9
		C. cujete	4x4 for shrubs	300	-	-
		L. leucocephala		300	-	-
				633		
A3	Pasture, trees, shrubs, and timber trees	*D. aristatum*	-	-	-	-
		P. maximum	-	-	-	-
		G. ulmifolia	16x16 for trees	11	13.2±1.1	43.3±6.7
		C. grandis		11	12.1±0.5	40.3±2.2
		A. saman		11	21.2±2.0	66.9±2.9
		C. cujete	4x4 for shrubs	300	-	-
		L. leucocephala		300	-	-
		P. quinata	16x16for timber trees	11	19.2±1.1	58.6±2.2
		S. macrophylla		11	12.3±1.5	27.3±1.9
				655		

* At planting the initial distance among trees was 8x8 m, four years later the trees were thinned to 16x16 m.
**DBH= diameter at breast height ± standard deviation

Soil sampling and testing

On June 2010, surface (0-5 cm) soil samples associated with each plant species were collected in the experimental plots. For this purpose, in each plot we selected at random 10 trees of each plant species, and four subsamples of the soil around their root system were collected. These 40 subsamples were thoroughly mixed to form a single soil sample per plant species per plot. In this way, 1560 soil subsamples were collected in the plots, which represented 39 soil samples (Table 2).

The soil samples were analyzed in the Soil and Plant Testing Laboratory of CORPOICA-Tibaitata at Mosquera, Colombia. Soil test were: soil pH (water, 1:2.5), phosphorus (Bray-II), calcium, potassium, and magnesium (1 M ammonium acetate), soil organic matter content (Walkley-Black), organic carbon in humic substances, and the E_4/E_6 ratio was measured in a spectrophotometer at 465 and 665 nm in the $NaHCO_3$ extract [29]. Details about soil analysis methods are available in Westerman [30].

Statistical analysis

Data were subjected to analysis of variance and mean separation by the Tukey test with P-value of 0.05. Statistical analyses were carried out with the software SAS version 9.2 (SAS Systems inc., North Carolina, USA).

Tabla 2. Number of soil subsamples collected and composite samples associated to plant species in silvopastoral systems in The Sinu River Valley, Colombia.

System	Composition	Plant species	No. subsamples per plant species in each plot	No. subsamples per plant species in each system	No. composite samples per system
A0	Pasture	*D. aristatum*	40	240	6
		P. maximum	40		
A1	Pasture and trees	*G. ulmifolia*	40	360	9
		C. grandis	40		
		A. saman	40		
A2	Pasture, trees, and shrubs	*G. ulmifolia*	40	360	9
		C. grandis	40		
		A. saman	40		
A3	Pasture, trees, shrubs, and timber trees	*G. ulmifolia*	40	600	15
		C. grandis	40		
		A. saman	40		
		P. quinata	40		
		S. macrophylla	40		
Total			520	1560	39

RESULTS

Soil pH

The soil pH values associated with *D. aristatum* (pH 5.5) and *P. maximum* (pH 5.9) were significantly (P <0.05) lower than the soil pH found associated with *G. ulmifolia* in the A2 and A3 systems (pH 6.4, 6.2) and *C. grandis* in the A3 system (pH 6.2) (Fig. 1a).

Soil phosphate

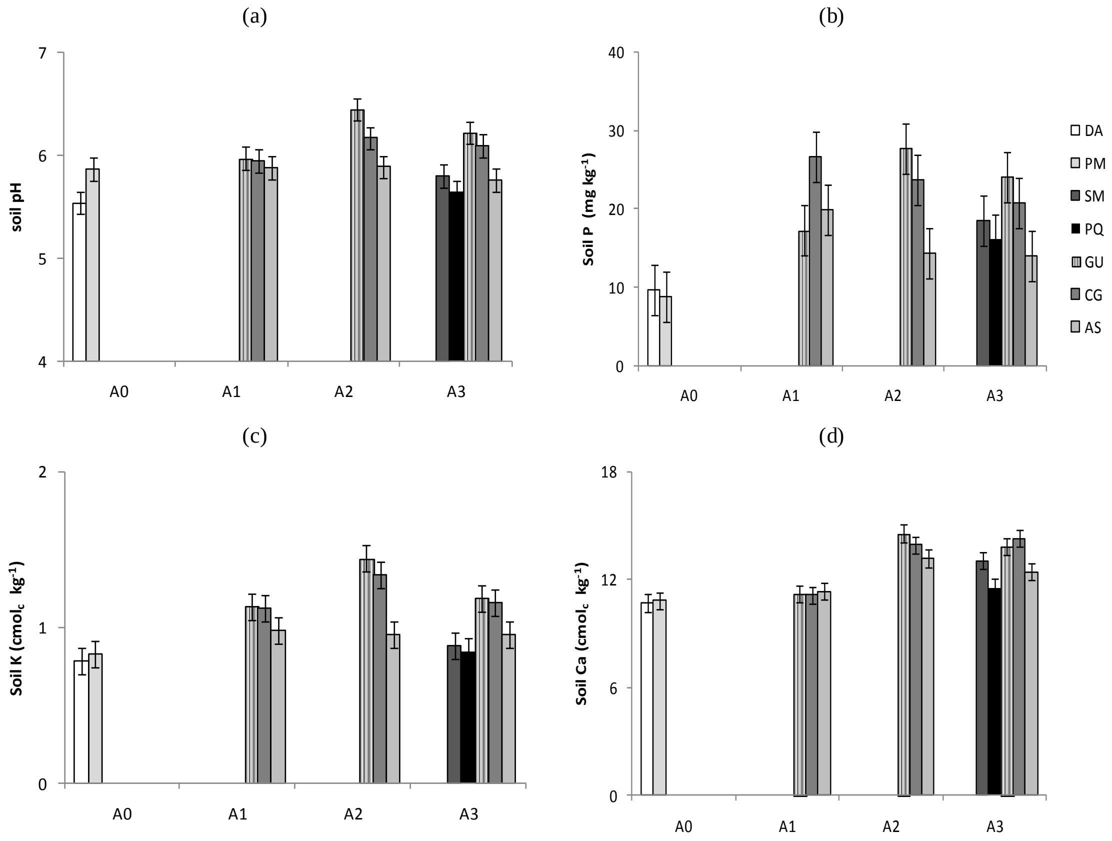
Consistently, the soil associated to the grasses had very low levels of available P (<10 mg kg^{-1}), which were significantly (P <0.05) lower than the soil associated to the trees. The highest soil P levels were detected with *G. ulmifolia* in the systems A2 y A3 (24-28 mg kg^{-1}) and *C. grandis* in the system A1 and A2 (24-27 mg kg^{-1}) (Fig. 1b).

Soil exchangeable bases

The level of soil exchangeable K^+ in the pasture (~0.8 $cmol_c$ kg^{-1}) was significantly lower than that associated with the trees, particularly with *G. ulmifolia* and *C. grandis* in the system A2 (1.3-1.4 $cmol_c$ kg^{-1}) (Fig. 1c). These differences represented 63-75% more exchangeable K^+ in the soil associated with these tree species than in the soils of the grasses.

The levels of exchangeable Ca^{2+} had a similar behavior to that for exchangeable K^+. Thus, the soil Ca^{2+} levels associated with the grasses *D. aristatum* and *P. maximum* (10.7 and 10.8 $cmol_c$ kg^{-1}) were significantly lower than those found in the soil associated with *G. ulmifolia* and *C. grandis* in systems A2 and A3 (13.8-14.6 $cmol_c$ kg^{-1}) (Fig. 1d). These differences represented 29-36% more exchangeable Ca^{2+} in the soil associated with these tree species than in the soil of the grasses.

In contrast, there were not significant differences in the levels of exchangeable-Mg^{2+} in the soil associated with the grasses and the tree species (Fig.1e). It is noteworthy that all soil samples collected had very high values of exchangeable Mg^{2+} (6.6-10.4 $cmol_c$ kg^{-1}).



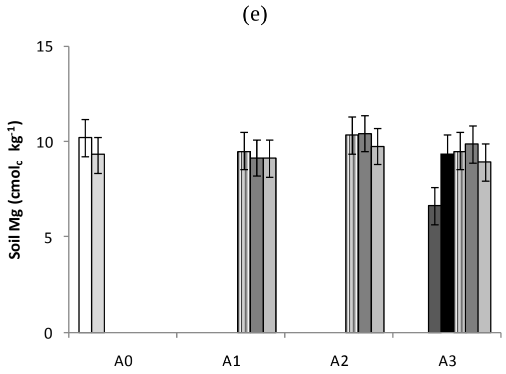


Fig. 1. Soil fertility parameters associated to pastures and tree species in multistrata silvopastoral systems in the Sinu valley, Colombia. Abbreviations= *D. aristatum* (DA), *P. maximum* (PM), *G. ulmifolia* (GU); *C. grandis* (CG); *A. saman* (AS); *P. quinata* (PQ); *S. macrophylla* (SM).

Soil organic matter content

There were significant differences ($P \leq 0.05$) in the soil organic matter content among soils associated with *C. grandis* in systems A2 and A3 (10.9%) and those associated with *P. quinata* in system A3 (7.6%) and *A. saman* in systems A1 and A3 (8.6-8.4%). The soil organic matter content in the pastures *D. aristatum* and *P. maximum* (8.9 and 9.3%) did not exhibit significant differences with those soils associated with the tree species (Fig. 2a).

Humic substances

There were not significant differences in the carbon content of humic substances and humic acids in the soil associated to tree species and grasses. The values fluctuated between 45.3-56.1% and 22.0-31.4%, respectively (Fig. 2b,c). The E_4/E_6 ratio in the humic substances ranged between 10.8 and 11.9;

however these values did not exhibit significant differences among soil samples associated to grasses and tree species (Fig. 2d).

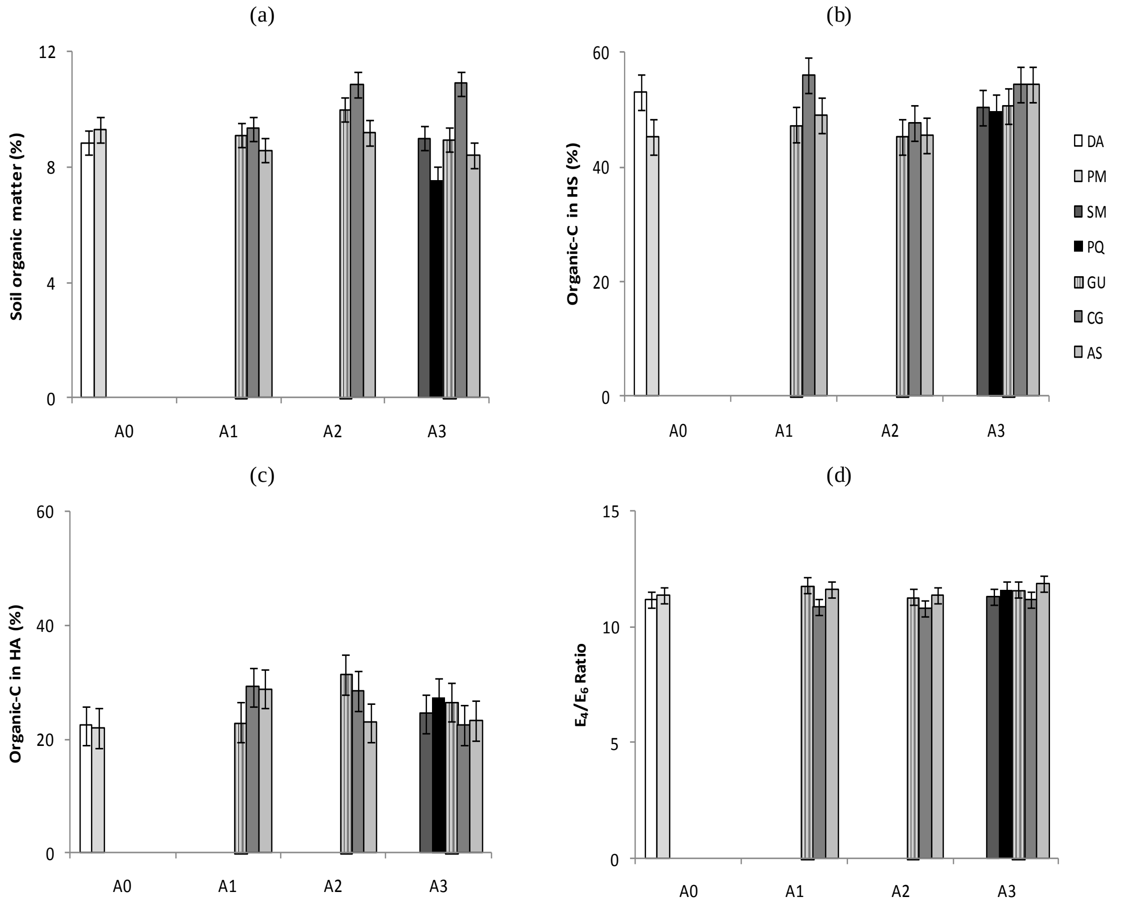


Fig. 2. Soil organic matter content, carbon in humic substances and E4/E6 ratio of soils associated with pastures and tree species in multistrata silvopastoral systems in the Sinu valley, Colombia. Abbreviations= *D. aristatum* (DA), *P. maximum* (PM), *G. ulmifolia* (GU); *C. grandis* (CG); *A. saman* (AS); *P. quinata* (PQ); *S. macrophylla* (SM). Carbon (C); humic substances (HS); humic acids (HA).

DISCUSSION

The results of this study demonstrate that some soil quality parameters (soil pH, P, K, Ca, and organic matter) were enhanced by the presence of tree species in silvopastoral systems. Similar results have been reported by Mafongoya et al. in South Africa [31], Fernandes et al. [32] in the Amazonas basin and Lemenih et al. [16] in Ethiopia. In this way, the soil pH and availability levels of P, K, and Ca associated with some tree species were significantly higher in comparison to those levels in the soil of a pasture with *D. aristatum* and *P. maximum*. The effects found were associated with the tree species involved rather than the sylvopastoral arrangement. It is noteworthy that the soil associated with *G. ulmifolia* in system A2 had around three times more P (28 mg kg^{-1}) than the soil in the pastures (*P. maximum*: 9 mg kg^{-1} and *D. aristatum:* 10 mg kg^{-1}). Also, the soil P associated with other tree species was on average twice that of the pastures. These results are consistent with high levels of litter production in the silvopastoral system as shown by some authors [33, 34, 35, 36, 37]. It is worth mentioning that *G. ulmifolia* was the tree species with higher annual P returns to the soil via leaf litter production [4, 6, 8], which can explain the higher level of soil bioavailable P in the soil associated with this species.

These results contrast the reports of Montagnini [38] in 5 year-old plantations of *Jacaranda copaia* and V*ochysia guatemalensis* where soil available P, K, and Ca were diminished. However, there were increases in soil available Ca under the trees *Terminalia amazonia* (0.5 $cmol_c$ L^{-1}) and *Virola koschnyi* (0.45 $cmol_c$ L^{-1}). Both species exhibited high levels of Ca in the leaves and high rates of litter production. Kershnar and Montagnini [39] reported that in a soil planted with *Hyeronima alchorneoides* higher levels of soil available Ca (0.65 $cmol_c$ L^{-1}), Mg (0.45 $cmol_c$ L^{-1}), and organic matter (0-5 cm: 12.7%, 5-15 cm: 6.2%) were detected than in plantations of *Vochysia ferruginea* (Ca: 0.5 $cmol_c$ L^{-1}, Mg: 0.25 $cmol_c$ L^{-1}, organic matter: 0-5 cm: 12.2%, 5-15 cm: 6.0%), *Balizia elegans* (Ca: 0.45 $cmol_c$ L^{-1}, Mg: 0.30 $cmol_c$ L^{-1}, organic matter: 0-5 cm: 9.0%, 5-15 cm: 6.0%), *Genipa americana* (Ca: 0.60 $cmol_c$ L^{-1}, Mg: 0.40 $cmol_c$ L^{-1}, organic matter: 0-5 cm: 9.0, 5-15 cm: 6.0%).

On the other hand, in studies conducted by Velasco et al. [40] in silvopastoral systems with the grass *Brachiaria humidicola* and *Acacia mangium* (at two densities: 120 and 240 trees ha^{-1}) the soil available P increased in the soil associated with *A. mangium* at the highest tree density (232 mg L^{-1}) relative to the lowest tree density (80 mg L^{-1}) respect to the soil under monoculture of *B. humidicola* (3 mg L^{-1}). It is evident that the tree density and the amount and quality of litter control the nutrient return into the soil and consequently the soil nutrient availability. *A. mangium* has been also used in land restoration given its capability to reactivate biogeochemical nutrient cycles in degraded soils via litter fall and decomposition [41, 42]. While in the silvopastoral systems of the current study the P return through the litter was 1-3 kg ha^{-1} yr^{-1}, in the pasture this was only 0.2-0.8 kg ha^{-1} yr^{-1}. We did not consider the nutrient return via animal excreta, which can constitute a significant P supply into the soil [43].

The low levels of soil available P found in the pastures of soils from the Sinu River Valley are surprising because these soils have been characterized with high soil fertility parameters, particularly P. However, these soils have been subjected for many decades, since the 1840´s [44], to a constant nutrient removal (for meat and milk production) without soil nutrient restitution with fertilizers. Over time, the soils have become depleted in some nutrients given their low soil P buffer capacity [45].

Parrotta [46] found that when the silvopastoral species *Casuarina equisetifolia, Eucalyptus robusta*, and *L. leucocephala* were grown concomitantly (*C. equisetifolia/E. robusta, C. equisetifolia/L. leucocephala, L. leucocephala/E. robusta*) the soil had higher total N, concentrations of nutrients (K, Mg, Na, Fe), and soil organic matter than when the species were grown in monoculture.

In the current study the soil organic matter content was higher with *C. grandis* and *G. ulmifolia*. Both tree species exhibited contrasting litter decomposition rates (*k*) [6], suggesting thus that the amount of litter production and their decay rates are controlling the soil nutrient availability. Similar results have been reported by Mafongoya et al. [31], Castellanos-Barliza and León [42], and Celentano et al. [47].

On the other hand, it is not surprising that in the current study there were not significant differences in the organic-C content of humic substances and humic acids and in the E4/E6 ratio in the soil associated with the different plant species considered (including the grasses). Under the soil and weather conditions studied (tropical dry forest), a dominance of mineralization over humification is expected. This was quite evident from other studies where we measured the rate of litter decomposition of several plant species (trees and grasses) with the litter-bag technique [6, 10]. Most of the litter materials were completely decomposed in one year or less. The values of the E4/E6 ratios (~11.0) indicate that the humic substances had a low degree of condensation of aromatic components [29] and low residence time of humic materials and a dominance of fulvic acids over humic acids [48].

Notably the changes observed in the current study were obtained 13 years after the establishment of the silvopastoral systems. It is expected that during the early stage of development (e.g., first three years) the fast growing trees removed part of the soil nutrient reserves and thus reduced their availability for crop roots [49]. However, once the canopy was very closed (4-5 years, depending on species and tree density) some trees acted as a self-nourishing system via litter production and decay. It is expected that in natural ecosystems, the organic matter decomposition is synchronized with the plant nutrient uptake and growth and thus N and other plant nutrients would be used efficiently [50]. However, in agroecosystems the release of nutrient (particularly N) is not in synchrony with the plant nutrient needs [51, 52, 53].

The pastures with only grasses depleted soil nutrients and acidified the soil; the effect is most dramatic in soil P availability since this element is below the critical level (<10 mg kg^{-1}), whereas other nutrients still had high availability. For this reason, to maintain adequate productivity it is necessary to apply N and P fertilizers to grasslands. The amounts of nutrients via fertilizers to be applied in the pastures are much higher than those for silvopastoral systems (e.g., N: 50 vs. 25 kg ha^{-1}; P_2O_5: 50 vs. 25 kg ha^{-1}, respectively) [54]. Undoubtedly, this can have an impact on production costs. On the other hand, the use of biofertilizers such as N_2 fixing bacteria, mycorrhizal fungi and P solubilizing microorganisms in the silvopastoral system with legume trees may provide several benefits [53, 55, 56, 57, 58]. In this regard it is relevant to mention that legume trees can also transfer fixed N_2 to associated grass via common mycorrhizal networks as reported by several authors [12, 13, 59], which account for others significant benefits of silvopastoral systems on soil functioning in the tropics [60, 61].

CONCLUSIONS

Over time the traditional system of livestock production based on only grasses has low return of soil nutrients and, consequently, the soil has been acidified and nutrient depleted. In contrast, after 13 years the silvopastoral systems contributed significantly to nutrient cycling via litter production and decomposition; as a result of that, these systems can maintain or increase soil reaction and soil quality parameters.

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