

Research Article

Silvopastoral Systems Enhance Soil Quality in Grasslands of Colombia

Judith Martínez,^{1,2} Yasmín S. Cajas,¹ Juan D. León,² and Nelson W. Osorio²

¹ CORPOICA Turipaná, Km. 13 vía Montería-Cereté, Córdoba, Colombia

² Universidad Nacional de Colombia, Calle 59 No. 63-20, 050034 Medellín, Colombia

Correspondence should be addressed to Juan D. León; jdleon@unal.edu.co

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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*.

1. 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 [3–6]. The major cause is overgrazing and lack of proper management practices such as monoculture of Gramineae versus plant diversity, adequate fertilization, soil conservation practices, and reduced tillage [7–10]. Consequently, over time, these soils exhibit high level of compaction (2.2–4.2 MPa) and low levels of plant nutrients (e.g., phosphate: $<10 \text{ mg kg}^{-1}$ and potassium: $<0.11 \text{ cmol}_c \text{ kg}^{-1}$) 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 ($<300 \text{ g day}^{-1}$), late age for slaughter (30–36 months), and high cost of production (US\$ 0.80 kg^{-1}) [6, 8].

As an alternatives, 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 [11–16]. Unfortunately, in the tropics, there are not sufficient data to support these claims on soil quality parameters [17–19] as it occurs in the temperate zone [20–22], which limits the widespread use of this strategy [23–25].

Our hypothesis in this study was that soil quality parameters (e.g., soil pH, soil organic matter, and 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 on 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.

2. Materials and Methods

2.1. 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 is 28°C, the air humidity is 81%, and potential evapotranspiration is 1240 mm

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	<i>D. aristatum</i>	—	—	—	—
		<i>P. maximum</i>	—	—	—	—
A1	Pasture and trees	<i>D. aristatum</i>	—	—	—	—
		<i>P. maximum</i>	—	—	—	—
		<i>G. ulmifolia</i>	16 × 16	11	12.2 ± 1.1	42.4 ± 6.7
		<i>C. grandis</i>		11	13.3 ± 0.5	36.3 ± 2.2
		<i>A. saman</i>		11/33	19.2 ± 2.0	68.0 ± 2.9
		<i>D. aristatum</i>	—	—	—	—
A2	Pasture, trees, and shrubs	<i>P. maximum</i>	—	—	—	—
		<i>G. ulmifolia</i>	16 × 16 for trees	11	12.8 ± 1.1	54.7 ± 6.7
		<i>C. grandis</i>		11	14.0 ± 0.5	38.6 ± 2.2
		<i>A. saman</i>		11	21.4 ± 2.0	67.3 ± 2.9
		<i>C. kujete</i>	4 × 4 for shrubs	300	—	—
		<i>L. leucocephala</i>		300/633	—	—
		<i>D. aristatum</i>	—	—	—	—
		<i>P. maximum</i>	—	—	—	—
A3	Pasture, trees, shrubs, and timber trees	<i>G. ulmifolia</i>	16 × 16 for trees	11	13.2 ± 1.1	43.3 ± 6.7
		<i>C. grandis</i>		11	12.1 ± 0.5	40.3 ± 2.2
		<i>A. saman</i>		11	21.2 ± 2.0	66.9 ± 2.9
		<i>C. kujete</i>	4 × 4 for shrubs	300	—	—
		<i>L. leucocephala</i>		300	—	—
		<i>P. quinata</i>		11	19.2 ± 1.1	58.6 ± 2.2
		<i>S. macrophylla</i>	16 × 16 for timber trees	11/655	12.3 ± 1.5	27.3 ± 1.9

* At planting, the initial distance among trees was 8 × 8 m; four years later, the trees were thinned to 16 × 16 m.

** DBH: diameter at breast height ± standard deviation.

per year. According to Holdridge [26], the ecological life-zone is tropical dry forest.

2.2. Silvopastoral Systems. For this study, we used the plots established by Cajas-Giron and Sinclair [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*, and *Albizia saman*; A1), trees and two shrubs (*G. ulmifolia*, *C. grandis*, *A. saman*, *Crescentia kujete*, and *Leucaena leucocephala*; A2), and trees, shrubs, and two timber trees (*G. ulmifolia*, *C. grandis*, *A. saman*, *C. kujete*, *L. leucocephala*, *Pachira quinata*, and *Swietenia macrophylla*; A3) (Table 1). The livestock feed directly on grasses and shrubs (*C. kujete* and *L. leucocephala*). Each experimental plot had a size of 100 × 200 m (2 ha) and three replicates (total of 12 plots, 24 ha).

2.3. Soil Sampling and Testing. In 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 was soil pH (water, 1:2.5), phosphorus (Bray-II), calcium, potassium, and magnesium (1M ammonium acetate); soil organic matter content (Walkley-Black), organic carbon in humic substances, and the E_4/E_6 ratio were 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].

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

3. Results

3.1. 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

TABLE 2: Number of soil subsamples collected and composite samples associated with plant species in silvopastoral systems in the Sinu River Valley, Colombia.

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

G. ulmifolia in the A2 and A3 systems (pH 6.4, 6.2) and *C. grandis* in the A3 system (pH 6.2) (Figure 1(a)).

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

3.3. Soil Exchangeable Bases. The level of soil exchangeable K^+ in the pasture ($\sim 0.8 \text{ cmol}_c \text{ kg}^{-1}$) was significantly lower than that associated with the trees, particularly with *G. ulmifolia* and *C. grandis* in the system A2 ($1.3\text{--}1.4 \text{ cmol}_c \text{ kg}^{-1}$) (Figure 1(c)). 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 of exchangeable K^+ . Thus, the soil Ca^{2+} levels associated with the grasses *D. aristatum* and *P. maximum* (10.7 and $10.8 \text{ cmol}_c \text{ kg}^{-1}$) were significantly lower than those found in the soil associated with *G. ulmifolia* and *C. grandis* in systems A2 and A3 ($13.8\text{--}14.6 \text{ cmol}_c \text{ kg}^{-1}$) (Figure 1(d)). 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 (Figure 1(e)). It is noteworthy that all soil samples collected had very high values of exchangeable Mg^{2+} ($6.6\text{--}10.4 \text{ cmol}_c \text{ kg}^{-1}$).

3.4. 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 (Figure 2(a)).

3.5. Humic Substances. There were not significant differences in the carbon content of humic substances and humic acids in the soil associated with tree species and grasses. The values fluctuated between 45.3–56.1% and 22.0–31.4%, respectively (Figures 2(b) and 2(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 with grasses and tree species (Figure 2(d)).

4. 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 Amazon 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 silvopastoral arrangement. It is noteworthy that the soil associated with *G. ulmifolia* in system A2 had around three times more P (28 mg kg^{-1})

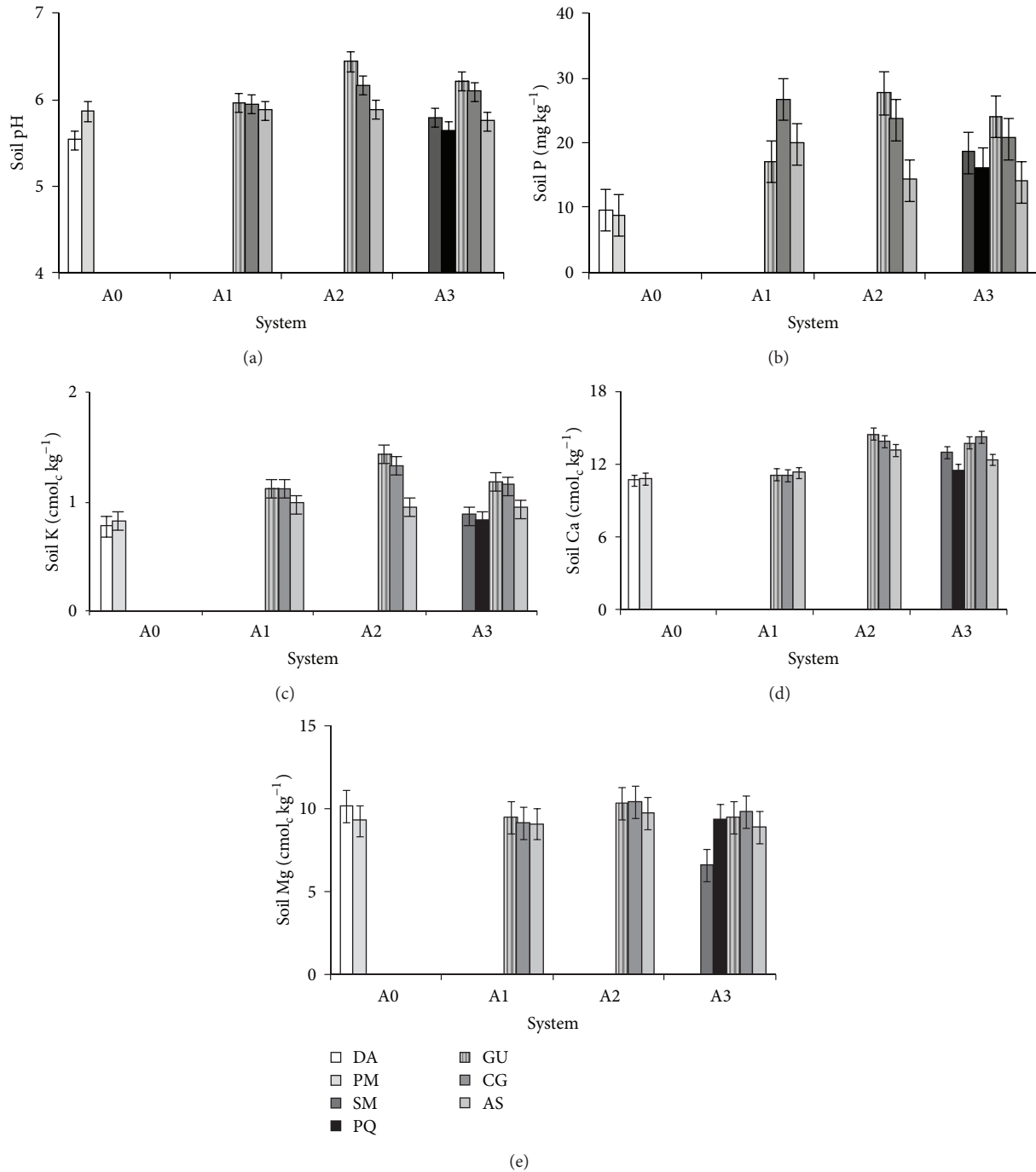


FIGURE 1: Soil fertility parameters associated with pastures and tree species in multistrata silvopastoral systems in the Sinu Valley, Colombia. Abbreviations: *D. aristatum* (DA); *P. maximum* (PM); *G. ulmifolia* (GU); *C. grandis* (CG); *A. saman* (AS); *P. quinata* (PQ); *S. macrophylla* (SM).

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 [33–37]. 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 *Vochysia guatemalensis* where soil available P, K, and Ca were diminished. However, there were increases in soil available Ca under the trees *Terminalia amazonia* ($0.5 \text{ cmol}_c \text{ L}^{-1}$) and

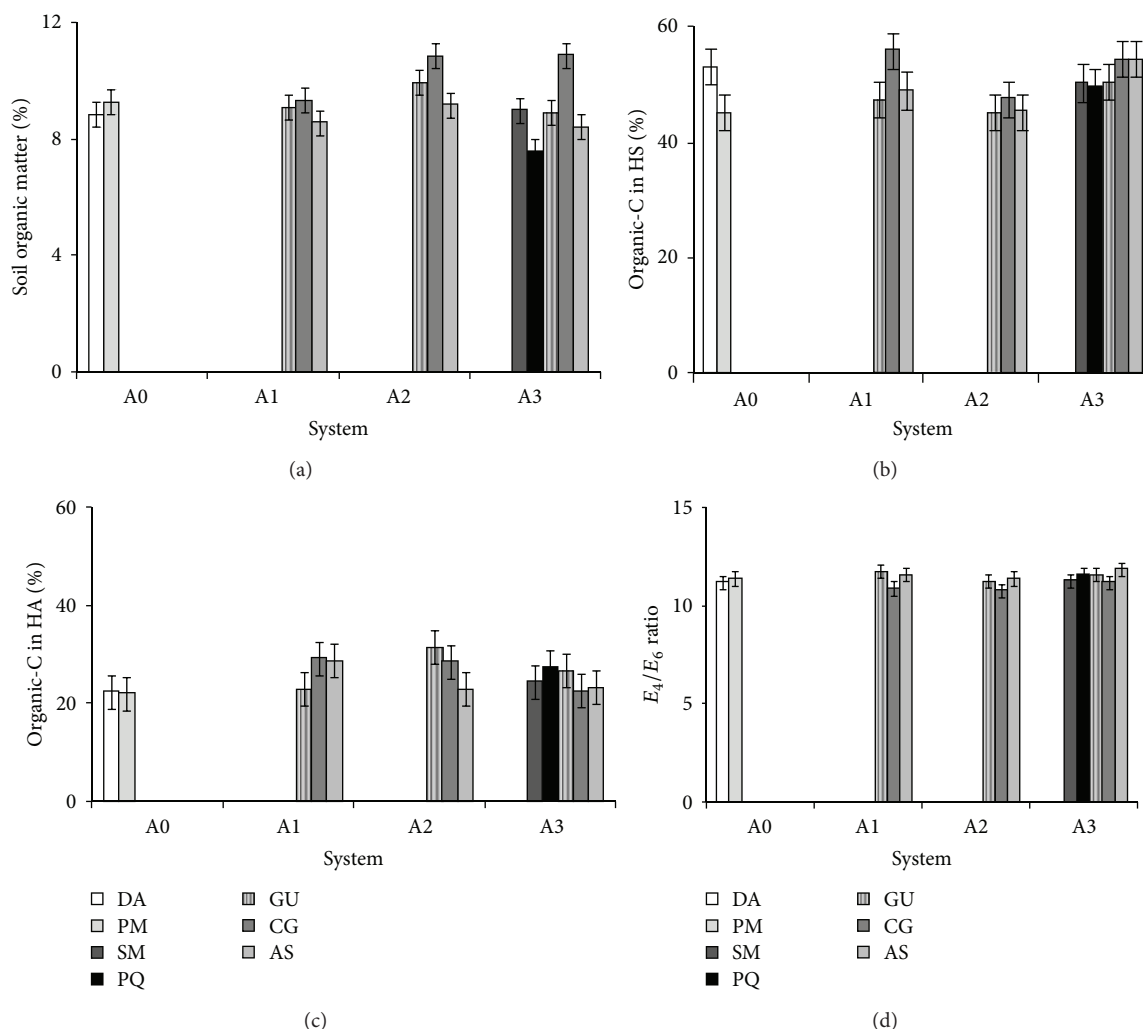


FIGURE 2: Soil organic matter content, carbon in humic substances, and E_4/E_6 ratio of soils associated with pastures and tree species in multistrata silvopastoral systems in the Sinu Valley, Colombia. Abbreviations: *D. aristatum* (DA); *P. maximum* (PM); *G. ulmifolia* (GU); *C. grandis* (CG); *A. saman* (AS); *P. quinata* (PQ); *S. macrophylla* (SM); carbon (C); humic substances (HS); humic acids (HA).

Virola koschnyi ($0.45 \text{ cmol}_c \text{ L}^{-1}$). Both species exhibited high levels of Ca in the leaves and high rates of litter production. Kershner and Montagnini [39] reported that, in a soil planted with *Hyeronima alchorneoides*, higher levels of soil available Ca ($0.65 \text{ cmol}_c \text{ L}^{-1}$), Mg ($0.45 \text{ cmol}_c \text{ L}^{-1}$), and organic matter (0–5 cm: 12.7%, 5–15 cm: 6.2%) were detected than in plantations of *Vochysia ferruginea* (Ca: $0.5 \text{ cmol}_c \text{ L}^{-1}$, Mg: $0.25 \text{ cmol}_c \text{ L}^{-1}$, organic matter: 0–5 cm: 12.2%, 5–15 cm: 6.0%), *Balizia elegans* (Ca: $0.45 \text{ cmol}_c \text{ L}^{-1}$, Mg: $0.30 \text{ cmol}_c \text{ L}^{-1}$, organic matter: 0–5 cm: 9.0%, 5–15 cm: 6.0%), and *Genipa americana* (Ca: $0.60 \text{ cmol}_c \text{ L}^{-1}$, Mg: $0.40 \text{ cmol}_c \text{ L}^{-1}$, 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})

with 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 $1\text{--}3 \text{ kg ha}^{-1} \text{ yr}^{-1}$, in the pasture this was only $0.2\text{--}0.8 \text{ kg ha}^{-1} \text{ yr}^{-1}$. 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 1840s [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*, and *L. leucocephala*/*E. robusta*), the soil had higher total N, concentrations of nutrients (K, Mg, Na, and 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], thus suggesting 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 Leon [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 E_4/E_6 ratio in the soil associated with the different plant species considered (including the grasses). Under the soil and weather conditions studied (tropical dry forest), 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 E_4/E_6 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 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 [51–53].

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 ($<10 \text{ mg kg}^{-1}$), 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 versus 25 kg ha^{-1} ; P_2O_5 : 50 versus 25 kg ha^{-1} , resp.) [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, 55–58]. 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 other significant benefits of silvopastoral systems for soil functioning in the tropics [35, 60].

5. 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.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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