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Original Article

Comprehensive evaluation of a silvopastoral system with Abarco (Cariniana pyriformis)

Evaluación integral de un sistema silvopastoril con Abarco (Cariniana pyriformis)

Cristian G. Palencia-Blanco[1] Gildardo E. Palencia Calderón[2] Luis E. Palencia Calderón[1]

[1]Instituto Universitario de la Paz – UNIPAZ, Grupo de Investigación en Innovación, Desarrollo Tecnológico y Competitividad en Sistemas de Producción Agroindustrial. Barrancabermeja, Santander, Colombia.
[2] Finca El Quinal del Tesoro, El Carmen de Chucurí, Santander, Colombia.

Abstract

Introduction: Silvopastoral systems (SPS) are a key strategy for restoring degraded soils and enhancing the sustainability of tropical livestock systems. In Colombia's Magdalena Medio region, the use of native forest species offers an opportunity to integrate production and conservation. In this context, an SPS incorporating Cariniana pyriformis (Abarco) as the main forest component was evaluated.
Objectives: To assess the performance of a silvopastoral system with Cariniana pyriformis on degraded soils in the Magdalena Medio region of Colombia, focusing on forest growth, forage production, and soil quality recovery.
Materials and Methods: The system included grasses (Brachiaria humidicola and Brachiaria decumbens) and forage shrubs (Morus alba L., Trichanthera gigantea, Gliricidia sepium), arranged in a functional design and managed under agroecological principles. Growth of Abarco trees was monitored over 40 months, along with forage production and several soil quality indicators (pH, organic matter, available phosphorus, soil macrofauna, and microbial activity).
Results: Abarco trees reached an average height of 6.36 m and a diameter at breast height (DBH) of 12.19 cm, with a mean diameter growth rate of 0.31 cm/month, allowing for timber harvesting projections at 12 years. The species showed good stem architecture and produced leaf litter rich in N, P, K, Ca, and Mg, contributing to nutrient recycling. Grasses yielded up to 14,960 kg fresh matter/hayear, and forage shrubs exceeded 13 kg fresh matter/shrubyear, with high palatability for livestock. Notable improvements in soil fertility were recorded, including increases in pH, organic matter, and available phosphorus, as well as enhanced soil macrofauna density and microbial activity.
Conclusions: The evaluated silvopastoral system provided both productive and ecological benefits, including biomass generation, functional soil restoration, and shade provision, which reduced animal heat stress and promoted biodiversity. This approach, known as the "Praderas de Felicidad" model, demonstrates the potential of SPS with native species as a viable strategy for transforming tropical livestock systems into more resilient, sustainable, and multifunctional systems.

Keywords: Silvopastoral systems, Native species, Forage biomass, Sustainable livestock, Cariniana pyriformis.

Resumen

Introducción: Los sistemas silvopastoriles (SSP) representan una estrategia clave para restaurar suelos degradados y mejorar la sostenibilidad de la ganadería tropical. En el Magdalena Medio colombiano, el uso de especies forestales nativas ofrece una oportunidad para integrar producción y conservación. En este contexto, se evaluó un SSP que incorpora a Cariniana pyriformis (Abarco) como componente forestal principal.
Objetivos: Analizar el desempeño de un sistema silvopastoril con Cariniana pyriformis en suelos degradados del Magdalena Medio colombiano, considerando indicadores de crecimiento forestal, producción forrajera y recuperación de la calidad del suelo.
Materiales y Métodos: El sistema incluyó gramíneas (Brachiaria humidicola y Brachiaria decumbens) y arbustos forrajeros (Morus alba L., Trichanthera gigantea, Gliricidia sepium), organizados en un diseño funcional y manejados bajo principios agroecológicos. Se evaluó el crecimiento del abarco durante 40 meses, así como la producción forrajera y diversos indicadores edáficos (pH, materia orgánica, fósforo disponible, macrofauna edáfica y actividad microbiológica).
Resultados: El abarco alcanzó un promedio de 6.36 m de altura total y 12.19 cm de DAP, con una tasa de crecimiento diametral de 0.31 cm/mes, lo que permite proyectar su aprovechamiento maderable a los 12 años. Mostró buena arquitectura de fuste y generó hojarasca con altos contenidos de N, P, K, Ca y Mg, favoreciendo el reciclaje de nutrientes. Las gramíneas produjeron hasta 14,960 kg FV/haaño, mientras que los arbustos forrajeros superaron los 13 kg FV/arbustoaño, con alta aceptación por parte del ganado. Se observaron mejoras en la fertilidad del suelo, con aumentos en pH, materia orgánica y fósforo disponible, además de una mayor densidad de macrofauna y actividad microbiológica.
Conclusiones: El sistema silvopastoril evaluado generó beneficios productivos y ecológicos, incluyendo generación de biomasa, recuperación funcional del suelo y provisión de sombra, lo que reduce el estrés térmico en el ganado y favorece la biodiversidad. Este modelo, conocido como "Praderas de Felicidad", demuestra el potencial de los SSP con especies nativas para transformar la ganadería tropical hacia prácticas más resilientes, sostenibles y multifuncionales.

Palabras clave: Sistemas silvopastoriles, Especies nativas, Biomasa forrajera, Ganadería sostenible, Cariniana pyriformis.

How to cite?

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Correspondence

cristian.palencia@unipaz.edu.co

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Why was this study conducted?

Traditional livestock farming has been one of the main drivers of soil degradation in the Colombian tropics, highlighting the need for more sustainable production strategies. One of the most promising alternatives is the implementation of silvopastoral systems (SPS), particularly those that integrate native tree species with both timber and ecological value. For this reason, the study focused on comprehensively evaluating the performance of abarco (Cariniana pyriformis) within an SPS established on degraded soils in the Magdalena Medio region, analyzing its forest growth, contribution to forage production, and effects on soil quality and edaphic biodiversity. The objective was to generate technical evidence to support the inclusion of native species in multifunctional livestock systems, contributing to ecological restoration and productive sustainability.

What were the most relevant findings?

Abarco trees reached, on average, 6.36 m in height and 12.19 cm in diameter at breast height (DBH) after 40 months, with a growth rate of 0.31 cm/month, allowing timber harvesting to be projected at 12 years. The species exhibited favorable stem architecture and contributed between 4.4 and 7.6 t/ha·year of biomass (litter), with high contents of nitrogen, potassium, and calcium, supporting nutrient recycling. The grasses Brachiaria humidicola and B. decumbens reached yields of 14,080 and 14,960 kg fresh forage/ha·year, respectively, while forage shrubs exceeded 13 kg fresh forage/shrub·year. Additionally, improvements in soil fertility were recorded, including increases in pH, organic matter, and available phosphorus, along with a rise in soil macrofauna density (from 11 to 95 individuals/m^2) and microbiological activity.

What do these findings contribute?

The research demonstrates that silvopastoral systems with abarco (Cariniana pyriformis) are a viable alternative for transforming tropical livestock systems by integrating native timber production, forage supply, and soil ecological recovery. The results highlight significant improvements in soil quality and biodiversity, while ensuring a diverse and resilient forage base. This approach, aligned with the "Happy Pastures" model, offers opportunities to diversify farmers' income, enhance animal welfare, and support the productive restoration of degraded lands—positioning itself as a sustainable and replicable strategy for livestock systems in similar tropical contexts.

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Introduction

The expansion of conventional livestock farming constitutes a primary driver of environmental degradation in Colombia, stemming from inappropriate land management, overgrazing, deforestation, and biodiversity loss. Currently, approximately 34.4 million hectares are allocated to this activity, although only 15 million possess suitable agroecological conditions, reflecting unsustainable pressure on ecosystems (1). This scenario necessitates a transition toward sustainable production models that enable natural resource conservation, climate change mitigation, and livestock productivity maintenance (2,3). In response, silvopastoral systems (SPS) emerge as integrated alternatives that combine trees, shrubs, and pastures in functional arrangements delivering economic, ecological, and social benefits (4,5). Multiple studies indicate that SPS enhance soil quality, increase forage availability, regulate microclimatic conditions, promote soil biodiversity, and generate timber or food products within sustainable livestock frameworks (6–8).

However, a major constraint to widespread SPS adoption in Colombia remains limited knowledge regarding native tree species' performance under livestock production conditions (9). Among species exhibiting high potential is Abarco (*Cariniana pyriformis*), a tropical tree of considerable timber value endowed with key functional traits including biomass production, soil fertility enhancement, and income-generation capacity through sustainable timber harvesting (3,10). Nonetheless, its integration into silvopastoral systems has been scarcely investigated, despite its viability as a strategy for advancing multifunctional productive systems targeting ecological restoration and sustainable livestock production.

Consequently, this study aimed to comprehensively evaluate a silvopastoral system incorporating the native timber species Abarco on degraded soils in Colombia's Magdalena Medio region. Three main components were addressed: tree growth and litterfall production of *C. pyriformis*, forage biomass yield (grasses and shrubs), and edaphic biodiversity as an indicator of soil health. The generated data seeks to provide empirical evidence supporting this species' potential in fostering multifunctional, resilient, and sustainable silvopastoral systems for tropical livestock regions.

Materials and Methods

Study location and system design

The study was conducted at "El Quinal del Tesoro" farm (FQT), situated in Campo 27's rural area within El Carmen de Chucurí municipality, Santander, Colombia (06°47'8.2"N; 73°36'7.5"W), at 306 meters above sea level. The climate corresponds to a warm-humid zone, characterized by an average annual temperature of 26.6 °C, 81% relative humidity, and 2,196 mm total annual precipitation. The silvopastoral system was established on previously degraded land through the introduction of the native timber species *Cariniana pyriformis* (Abarco), integrated with forage grasses (*Brachiaria humidicola* and *Brachiaria decumbens*) and multipurpose shrubs (*Trichanthera gigantea*, *Morus alba* L., and *Gliricidia sepium*). The spatial arrangement comprised triple tree rows forming live barriers, configured in a 4 × 4 × 4 × 26 m spacing pattern, achieving a planting density of 320 trees per hectare. Within two of the 26-m-wide inter-barrier spaces, *Brachiaria humidicola* and *Brachiaria decumbens* grasses were established using 3 kg of seed per strip, with an estimated 70% germination rate. In the third 26-m-wide space, forage shrubs were planted across 16 rows

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distributed as follows: five rows of *Gliricidia sepium* (Matarratón), six rows of *Morus alba* L. (Morera), and five rows of *Trichanthera gigantea* (Aro), resulting in estimated planting densities of 340, 408, and 340 shrubs per species, respectively.

Agronomic management of the silvopastoral system

During the establishment of the system, agronomic practices were implemented to improve soil conditions and facilitate the successful establishment of the plant species. Each planting hole for both trees and shrubs were amended with 150 g of dolomitic lime and 1 kg of composted organic matter. Weed control was carried out through six annual clearings (manual weeding) around the trees, four mechanical cuttings using a brush cutter, and two strip applications of herbicide. Additionally, formative pruning was performed on the Abarco trees starting in the third year, removing bifurcations and lower branches without exceeding 40% of the crown volume.

Evaluation of forest growth of Abarco

The growth of *Cariniana pyriformis* (Abarco) trees was evaluated by measuring total height (h) and diameter at breast height (DBH) over a 40-month period. Measurements were conducted at six-month intervals starting from system establishment, employing a graduated pole for height and a vernier caliper for DBH (11). Three repetitions were recorded per tree at randomly selected positions within the plot. Based on these measurements, the absolute growth rate (AGR) for height and diameter was calculated, expressed in cm/month. This rate served to project the time required to reach the minimum commercial DBH of 40 cm. Additionally, formative pruning was implemented starting in the third year to promote a single, straight main stem per tree by eliminating apical bifurcations and competing branches.

Litterfall characterization

To quantify litterfall biomass and its nutritional contribution per hectare, samples were collected at 24- and 42-months post-establishment. Litter sampling occurred biannually. Collected samples were sorted, weighed, and stored in labeled paper bags. These were then dried at 70 °C for 72 hours in an ACEQ forced-air oven. Total concentrations of nitrogen (N), phosphorus (P), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), sulfur (S), iron (Fe), copper (Cu), manganese (Mn), zinc (Zn), and boron (B) were quantified. Biomass per hectare was subsequently calculated for each six-month interval and aggregated annually.

Forage biomass estimation

The grass biomass assessment was performed using a 1 m² quadrat, thrown six times per pasture along zigzag transects. Fresh forage (FF) was cut at 5 cm above the soil surface and weighed using a field scale. Production was expressed in kg FF/ha, applying a 20% correction factor for trampling losses. For shrubs, six individuals per species were randomly selected at 42 months of age. Each plant was harvested completely, separating leaves and tender stems, which were weighed separately. Values were expressed in kg FF/shrub·year.

Soil chemical analysis

Composite soil samples were collected at a depth of 0–20 cm at two time points: at the beginning of the system's establishment (year 1) and after four years of development. For each sampling,

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subsamples were taken along zigzag transects within each plot and combined to form one composite sample per treatment. The samples were air-dried, sieved (2 mm mesh), and sent to the laboratory for physicochemical analysis. The following variables were determined using standard methods of the Instituto Geográfico Agustín Codazzi, soil pH in water (1:2.5), exchangeable aluminum (Al^{3+}), organic matter content (OM), cation exchange capacity (CEC), available phosphorus, potassium (K), calcium (Ca), and magnesium (Mg).

Soil biodiversity assessment

Soil macrofauna was evaluated using monoliths of 25 × 25 × 30 cm, following the methodology of Silva-Olaya et al., (7). The upper 10 cm layer was analyzed using Berlese funnels to identify microinvertebrates, while the remaining volume was manually explored to collect macroinvertebrates. These were classified to taxonomic order and their density recorded as individuals per square meter (ind/m²) (12). For the soil microbiological analysis, composite samples were taken at a depth of 10 cm by combining three subsamples per sampling point. Specific culture media were used to quantify aerobic mesophilic bacteria, filamentous fungi, and actinomycetes. The plate dilution method was applied to express the results in colony-forming units per gram of soil (CFU/g). The analysis was conducted at the beginning of the system and again at year 4, allowing for the evaluation of the SPS's effect on soil biological activity (10,13,14).

Results and Discussion

Forest growth of Abarco and litter production

Figure 1 presents the results of forest growth in terms of total height and diameter at breast height (DBH) of Abarco trees. 40 months after the establishment of the silvopastoral system, Abarco trees reached an average height of 6.36 m and an average DBH of 12.19 cm. These values indicate favorable growth performance under degraded soil conditions, considering that the species is known for its slow growth during the initial development stages.

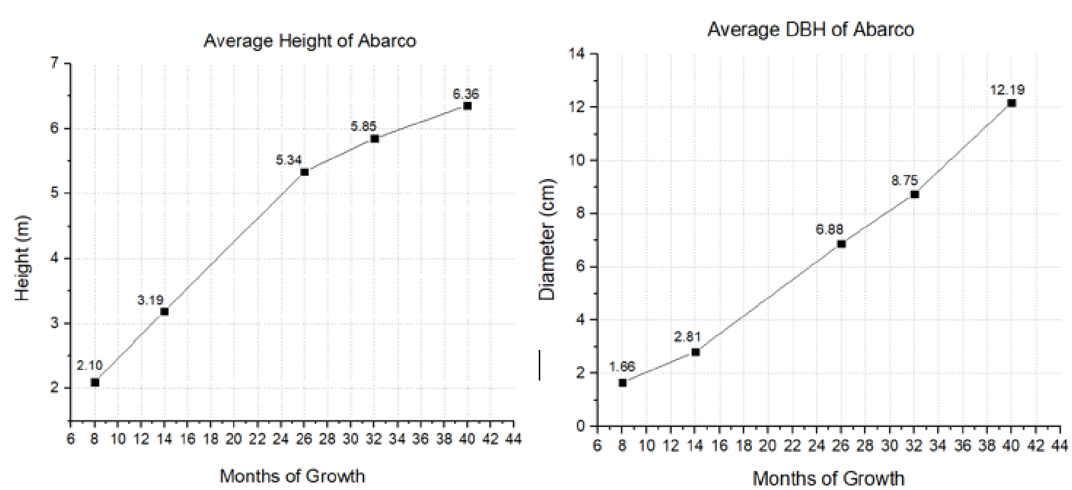

Figure 1. Average height and diameter at breast height (DBH) of Abarco trees in the silvopastoral system. Source: Authors

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The formation of a single, straight main stem was achieved in more than 80% of the individuals evaluated, because of formative pruning carried out from the third year onward. This aerial architecture pattern is desirable from a silvicultural perspective, as it optimizes merchantable timber volume and reduces stem defects—key attributes for the future valuation of the species as high-quality commercial wood (15). Figure 2 shows the absolute growth rate in height and diameter, which averaged 14.75 cm/month and 0.31 cm/month, respectively, under planting densities arranged in triple rows. These growth rates suggest that Abarco would reach the minimum harvestable diameter (40 cm DBH) in approximately 12 years, assuming an estimated annual diameter increment of 3.72 cm. Additionally, it was observed that the greatest height development occurred during the first 26 months, after which it slowed down, while the diameter continued to increase at a steady rate-behavior characteristic of medium-growth timber species adapted to limiting site conditions (16).

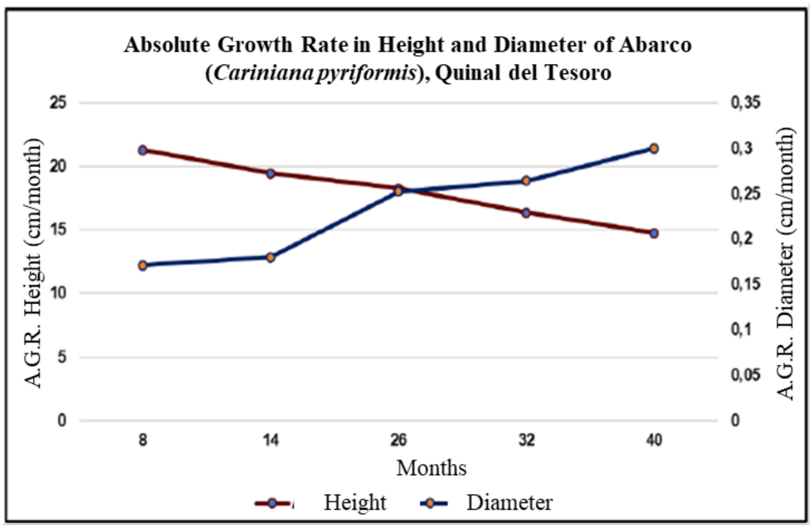

Figure 2. Absolute growth rate in height and DBH of Abarco in the silvopastoral system (SPS).
Source: Authors

Figure 3 shows the biomass production in the "Happy Pastures" system. It was observed that 320 Abarco trees generated a significant biomass contribution, ranging from 4.4 to 7.6 ton/ha·year (litterfall) between the first and second sampling periods. The difference is associated with the system's age: the first sampling was conducted 24 months after planting, and the second at 42 months. The total amount of biomass deposited on the soil increased as the system matured, due to the larger volume of the trees as age progressed (17). Abarco has demonstrated the ability to produce biomass even under low-nutrient soil conditions, contributing mineral elements that are naturally deposited on the soil surface each year through litterfall. This material forms the litter layer, which undergoes decomposition and leads to the gradual release of nutrients (13,17). In addition, the mineralization of this material and its availability for reabsorption into the system constitute a key mechanism for nutrient recycling. Another important factor is planting density, which also plays a decisive role in the amount of biomass deposited on the soil. In summary, the higher the density of Abarco trees, the greater the biomass production (18,19).

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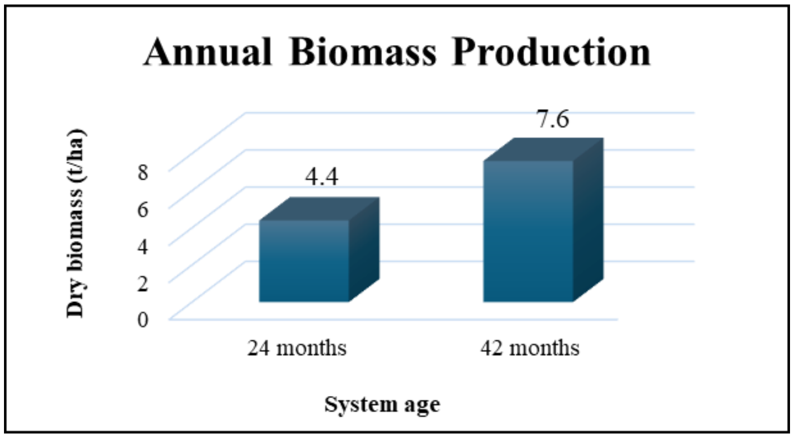

Figure 3. Biomass production in the "Happy Pastures" system, years 2015 and 2017. Source: Authors

Litter plays a crucial role in providing soil cover, modifying the edaphic environment as it decomposes and becomes a major source of organic matter that activates the biogeochemical cycle (7,17). Functionally, a significant litter cover was observed beneath the tree canopy at four years of age, indicating an active dynamic of organic residue input. The chemical analysis of the litter revealed concentrations of essential nutrients such as nitrogen (13.3 g/kg), phosphorus (1.1 g/kg), potassium (9.2 g/kg), calcium (19.7 g/kg), and magnesium (4.5 g/kg). These values fall within the reported range for forest species with high nutrient recycling capacity (9), and suggest that Abarco can contribute significantly to improving soil fertility through the return of foliar biomass. These findings support the use of Abarco as a structural species in multifunctional silvopastoral systems not only for its native timber potential, but also for its role as a facilitator of ecological restoration processes, such as shade provision, moisture retention, and nutrient restitution to the soil through litterfall (3,9).

Nutrient contribution from Abarco biomass

Plant biomass represents the main nutrient reservoir within the "Happy Pastures" system. Therefore, understanding the nutrient cycling process requires quantifying ecosystem biomass per unit area (10). The amount of nutrients returned to the soil through biomass is directly related to the quantity of falling residues and their nutrient concentration, which varies depending on the species and age (20)[1]. According to preliminary results, Table 1 shows that the highest nutrient contribution per ton of biomass per hectare per year was 15.54 kg of nitrogen (N), followed by 8.35 kg of calcium (Ca) and 6.62 kg of potassium (K). Among the micronutrients, iron (Fe) and zinc (Zn) showed the highest concentrations in the litter, with 1.4 kg/t·ha·year and 0.6 kg/t·ha·year, respectively.

Table 1. Nutrient contribution (kg per ton of biomass per hectare per year)

Element	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Fe**	**Zn**	**B**
k**g/**t*h**a*year**	15.54±0.65	2.28±0.12	6.62±0.70	8.35±1.23	1.98±0.15	3.96±0.42	1.4±0.36	0.6±0.09	0.2±0.01

Source: Authors

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The continuous fall of leaves, seeds, branches, and root mortality (especially fine roots) constitutes a constant input of organic matter and nutrients to the soil. After decomposition and mineralization, these materials can be absorbed by pasture species. Additionally, the type of tissue determines the amount of nutrients returned, as the concentration of mineral elements is highest in leaves, followed by branches, stems, and roots (6,7,13). For the system to function optimally and for nutrient recycling to be efficient, it is essential to understand the characteristics of each component species—specifically, which species to combine. This is because the system requires plants with varied foliar nutrient contents and different decomposition rates (fast, medium, and slow) to ensure nutritional balance, a constant nutrient flow, and reduced losses. The management of grasses in association with trees allows a significant portion of the nutrients extracted from the soil solution to return via foliage deposition, grazing residues, or pruning material left on the soil surface. This greater input of organic matter contributes to the transformation of the soil's physical properties, especially its structure (3,7,21). Figure 4 shows part of the spatial arrangements established in the "Happy Pastures" system.

Figure 4. Landscapes of the "Happy Pastures" system at Quinal del Tesoro. Source: Authors

Forage biomass production

Table 2 presents the biomass production of forage shrubs, with leaves and tender stems measured separately. The availability of leaves per shrub was 7.6 kg FF/year for *Trichanthera gigantea* (Aro), 8.1 kg FF/year for *Morus alba* L. (Morera), and 6.7 kg FF/year for *Gliricidia sepium* (Matarraton). Stem production was also significant, with values of 5.9 kg FF/year for both Aro and Morera, and 5.1 kg FF/year for Matarraton. Although this study did not directly evaluate animal intake, field observations indicated a higher preference of livestock for Morera, consistent with findings by Vargas and Estrada (22), who reported greater consumption of Morera foliage, followed by Matarraton and, to a lesser extent, Aro.

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Table 2. Fresh forage (FF) production per forage shrub

No. Sample/shrub	Aro (*Trichanthera gigantea*)		Morera (*Morus alba L*)		Matarraton (*Gliricidia sepium*)	
	Leaves (kg)	**Stems (kg)**	**Leaves (kg)**	**Stems (kg)**	**Leaves (kg)**	**Stems (kg)**
1	2.2	1.8	2.5	1.7	1.8	1.3
2	1.9	1.5	2.2	1.4	1.6	1.2
3	1.7	1.4	1.9	1.3	1.4	1
4	1.8	1.4	1.9	1.4	1.7	1.2
5	2	1.5	1.8	1.4	1.7	1.4
6	1.8	1.3	1.8	1.5	1.9	1.5
Average kg/shrub	1.9±0.18	1.5±0.17	2.0±0.28	1.5±0.14	1.7±0.17	1.3±0.18
Average kg/year	7.6±0.72	5.9±0.69	8.1±1.10	5.8±0.55	6.7±0.69	5.1±0.70

Source: Authors

According to the values presented in Table 2, the highest yield of edible forage biomass (leaves + tender stems) was obtained from *Morus alba* (Morera), with a total availability of 13.9 kg FF/shrub·year, followed by *Trichanthera gigantea* (Aro) with 13.5 kg FF/shrub·year, and finally *Gliricidia sepium* (Matarraton), which reached an average of 11.8 kg FF/shrub·year. Several studies (16,22,23) indicate that these shrub species have high forage potential in both leaves and young stems, and that their nutritional qualities and palatability make them excellent supplements to the basic feed supply in silvopastoral systems. They can enhance the diet of grazing livestock and provide a reliable volume of forage during periods of scarcity. This study demonstrated that the forage species not only adapted well to the agroclimatic conditions but also tolerated the agronomic management practices to which they were subjected. The higher forage use may be linked to specific characteristics related to biomass production or palatability for the animals (22). A promising approach is the promotion of forage trees in mixtures or with diverse foliar types, as positive results have shown that the consumption of mixed shrubs is greater than that of individual species alone.

Regarding the herbaceous base of the system, *Brachiaria humidicola* and *B. decumbens* showed an average fresh forage yield of 1.76 kg/m² and 1.87 kg/m² per cut, respectively, as shown in Table 3.

Table 3. Fresh forage yield (kg/m²·cut) in pastures of the silvopastoral system (SPS)

No. Sample	Grasses	
	Humidicola (kg/m²)	**Decumbes (kg/m²)**
1	1.55	1.65
2	1.71	1.85
3	1.66	1.70
4	1.94	2.01
5	1.80	1.75
6	1.88	2.23
Average ± SD	1.76±0.15	1.87±0.22

Source: Authors

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By extrapolating these values to one hectare and applying a 20% correction factor for trampling losses, the estimated annual yields were 14,080 kg FF/ha for *B. humidicola* and 14,960 kg FF/ha for *B. decumbens*. These results reflect good adaptation of both species to the site's edaphic conditions and confirm their role as an efficient forage base within the system. The production difference between the two species was 8%, with *B. decumbens* showing the highest yield. This performance may be attributed to its well-documented capacity to adapt to acidic soils with low fertility and loamy-sandy textures—conditions prevalent in the study area. The values obtained fall within the ranges reported for silvopastoral systems on medium fertility soils (24,25) and exceed the typical yields found in degraded pastures lacking tree cover. This suggests a positive effect of the system on vegetation cover, microclimate regulation, and nutrient recycling efficiency. The interaction among grasses, shrubs, and trees within the system ensured sustained availability of edible biomass, even under edaphic limitations, promoting the complementary integration of diverse forage sources.

Soil quality and soil biodiversity

The establishment of the silvopastoral system with *Cariniana pyriformis* on degraded soils in the Magdalena Medio region led to notable improvements in the soil's physicochemical properties after four years of implementation. Table 4 shows a comparison of soil analyses conducted at two different time points.

Table 4. Chemical characterization of the soil in 2013 and 2017 in the silvopastoral system at the Quinal del Tesoro farm.

No. Sampling	pH	Al meq/100 g	% Organic Matter	P (mg/kg)	cmol/kg				
					K	Ca	Mg	Na	CIC
Sample 2013	4.5	4.6	2.0	2.10	0.09	1.35	0.26	0.05	3.70
Sample 2017	4.8	0.5	3.0	4.05	0.13	1.28	0.31	0.05	3.28

Source: Authors

Soil pH increased from 4.5 to 4.8, reflecting a reduction in acidity, while exchangeable aluminum content decreased significantly from 4.6 to 0.5 meq/100 g, thereby enhancing nutrient availability and root development of the established species (26). Organic matter content rose from 2.0% to 3.0%, and the cation exchange capacity (CEC) increased from 8.5 to 14.4 meq/100 g, indicating a greater ability of the soil to retain and supply nutrients (27). In addition, there was an increase in phosphorus (from 5.6 to 12.2 mg/kg), potassium (from 0.23 to 0.45 cmol/kg), calcium (from 0.35 to 2.65 cmol/kg), and magnesium (from 0.22 to 1.52 cmol/kg) levels (20,28). These changes can be attributed to the combined effect of biomass return through abarco litterfall, permanent vegetative cover, and the reduction of runoff and erosion. This type of improvement has been documented in silvopastoral systems by various authors, who emphasize the role of trees in nutrient recycling and stabilization of edaphic conditions (3,25). The chemical recovery of the soil was accompanied by a positive response in soil biodiversity, as shown in Figure 5.

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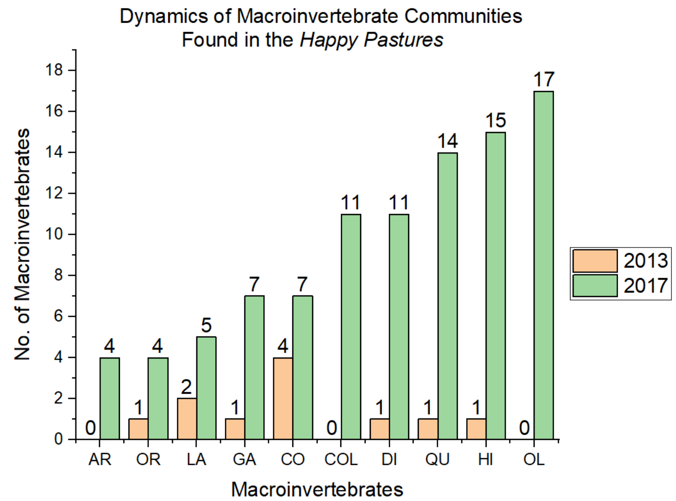

Figure 5. Number of macroinvertebrates found in the soil of the "Happy Pastures" system. Years 2013–2017. AR: Arachnids; OR: Orthopterans; LA: Larvae; GA: Gastropods; CO: Coleopterans; COL: Collembolans; DI: Diplopods; QU: Chilopods; HI: Hymenopterans; OL: Oligochaetes. Source: Authors

The density of soil macrofauna increased from 11 to 95 individuals/m² between the first and fourth year, with notable representation of *Oligochaetes* (earthworms), *Hymenopterans* (ants, wasps), *Chilopods* (centipedes), *Diplopods* (millipedes), and *Collembolans* functional groups that are indicative of active and healthy soils (7,29). The abundant presence of earthworms suggests improvements in soil structure, aeration, and organic matter mineralization processes. This increase in macroinvertebrates is associated with greater vegetative cover, litter deposition, and the absence of intensive mechanical disturbances (10,12). Regarding microbiological analyses, the results showed an increase in soil biological activity. Table 5 presents the microbial counts (fungi, bacteria, and actinomycetes) before and after the establishment of the silvopastoral system.

Table 5. Microorganism content in CFU/g of soil before and after the establishment of the silvopastoral system

Microorganism	**Concentration (CFU/g of soil)**	
	Sample before SPS	**Sample after SPS**
Fungi	4.36×10^4	5.1×10^4
Bacteria	1.3×10^7	4×10^7
Actinomycetes	2.25×10^4	3.6×10^4

Source: Authors

Aerobic mesophilic bacteria increased from 1.3×10^7 to 4.0×10^7 CFU/g, actinomycetes from 2.25×10^4 to 3.6×10^4 CFU/g, and filamentous fungi from 6.1×10^4 to 8.2×10^4 CFU/g. These results indicate an activation of soil microbial metabolism and improved conditions for the decomposition of organic matter and nutrient cycling. The increase in beneficial microorganisms is closely associated with the continuous input of plant residues, canopy shade, and enhanced soil microclimatic conditions (10,13,30). The findings demonstrate that the silvopastoral system with

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Abarco fostered partial soil recovery in terms of both fertility and biological diversity. This synergy between biotic and abiotic components contributes to the provision of essential ecosystem services such as soil formation and conservation, nutrient recycling, and the regulation of biogeochemical processes—positioning the system as an effective strategy for the productive restoration of tropical grazing lands.

Conclusions

The *Cariniana pyriformis* based silvopastoral system established on degraded soils in Colombia's Magdalena Medio region demonstrated efficacy in integrating ecological restoration with sustainable livestock production. Abarco exhibited favorable growth performance and architectural form, showing medium-term timber potential while providing significant nutrient-rich litterfall contributions. The forage base comprising adapted grasses and multipurpose shrubs ensured consistent edible biomass supply despite high acidity and low fertility conditions. This diversified configuration enhanced food system resilience and improved animal welfare by mitigating thermal stress through shade provision.

Substantial soil quality improvements were documented: elevated pH, increased organic matter, enhanced nutrient availability, alongside greater macrofauna abundance and heightened microbiological activity. These transformations reinforce the system's capacity to deliver key ecosystem services, particularly soil regulation and edaphic biodiversity enrichment.

Aligned with the "Happy Pastures" approach, this model facilitates diversified revenue streams from timber, forage, and ancillary products while concurrently advancing habitat conservation and transitioning tropical livestock systems toward resilient, multifunctional, and environmentally responsible frameworks.

CrediT authorship contribution statement

Conceptualization - Ideas: Cristian Giovanny Palencia Blanco Gildardo Efraín Palencia Calderón. Data Curation: Cristian Giovanny Palencia Blanco, Gildardo Efraín Palencia Calderón, Luis Enrique Palencia Calderón. Formal analysis: Cristian Giovanny Palencia Blanco, Gildardo Efraín Palencia Calderón. Financing: Luis Enrique Palencia Calderón, Gildardo Efraín Palencia Calderón. Investigation: Cristian Giovanny Palencia Blanco, Gildardo Efraín Palencia Calderón, Luis Enrique Palencia Calderón. Methodology: Gildardo Efraín Palencia Calderón, Luis Enrique Palencia Calderón, Cristian Giovanny Palencia Blanco. Project Management: Gildardo Efraín Palencia Calderón, Luis Enrique Palencia Calderón. Resources: Gildardo Efraín Palencia Calderón, Luis Enrique Palencia Calderón. Software: Cristian Giovanny Palencia Blanco, Gildardo Efraín Palencia Calderón. Supervision: Cristian Giovanny Palencia Blanco, Gildardo Efraín Palencia Calderón, Luis Enrique Palencia Calderón. Validation: Cristian Giovanny Palencia Blanco, Gildardo Efraín Palencia Calderón, Luis Enrique Palencia Calderón. Writing - original draft - Preparation: Cristian Giovanny Palencia Blanco, Gildardo Efraín Palencia Calderón, Luis Enrique Palencia Calderón. Writing - revision and editing - Preparation: Cristian Giovanny Palencia Blanco. Gildardo Efraín Palencia Calderón, Luis Enrique Palencia Calderón.

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