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Agroforestry as a strategy for soil conservation in Colombia

La Agroforestería como estrategia para la conservación del suelo en Colombia

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ABSTRACT

In the tropical region of Colombia, land use and the expansion of the agricultural frontier are rapidly increasing, leading to declines in soil quality and health. Agroforestry has recently been proposed as a sustainable agricultural system that provides ecosystem services such as ecosystem restoration and soil conservation. In this context, a synthesis of the ecosystem services of agroforestry was carried out, focusing on the contributions of tree diversification and its relationship with soil conditions. The findings indicate that agroforestry systems directly provide organic matter through leaf litter, which contributes to macrofaunal richness and increases the availability of N, K, P, Mg, and Ca. Moreover, soils in agroforestry systems (SAF) represent important carbon sinks. Accordingly, the present study aims to analyze the contribution of SAF to soil conservation, as well as its role in promoting increases in arthropod and vertebrate populations and in regulating water and nutrient cycles.

Key words: agroforestry systems; ecosystem services; fertilization; macrofauna; management practices; soil stability

RESUMEN

En la región tropical de Colombia, el uso del suelo y la extensión de la frontera agrícola están aumentando rápidamente, lo que conduce a disminuciones en la calidad y salud del suelo. La agroforestería ha sido recientemente propuesta como un sistema agrícola sostenible que provee servicios ecosistémicos tales como restauración de ecosistemas y conservación del suelo. En este contexto, se realizó una síntesis de los servicios ecosistémicos de la agroforestería basados en los aportes de la diversificación arbórea y su relación con el estado del suelo. Se encontró que los sistemas agroforestales aportan de manera directa materia orgánica mediante la hojarasca que contribuye a la riqueza de macrofauna, la disponibilidad de N, K, P, Mg y Ca, sumado que los suelos de los SAF representan importantes sumideros de carbón. En este sentido, el presente estudio tiene como objetivo analizar el aporte de los PBS en la conservación del suelo, así como su rol en promover el incremento de artrópodos y vertebrados, y en regular el agua y los nutrientes.

Palabras Claves: estabilidad de suelo; fertilización; macrofauna; prácticas de manejo; servicios ecosistémicos; sistemas agroforestales

INTRODUCTION

This article aims to provide theoretical insights and present the results of research conducted following the implementation of Agroforestry Systems (SAF) for soil conservation as an ecosystem service. Emphasis is placed on the interaction between soil components within an SAF, considering biodiversity as well as the chemical and physical properties of the soil. Drawing on a literature review from various databases, this paper discusses the challenges faced by SAF in their design, implementation, and management, with the aim of enhancing soil conservation and, consequently, improving system productivity. It is crucial to understand the ongoing degradation of agricultural soils and the importance of conserving and maintaining their quality as fundamental resources for global agricultural production.

Soils are the lifeline for the development of plants, organisms, and agricultural production systems (Roy *et al.*, 2018; Bulgakov *et al.*, 2018). However, they have been affected by the loss of vegetation cover, mainly due to deforestation. The large-scale conversion of forests into monocultures is a response to anthropogenic disturbances and soil quality constraints, compounded by the fragility of physical, chemical, and biological properties (Saavedra-Mora *et al.*, 2019; Rinot *et al.*, 2019). The loss of soil quality has led to extensive areas of unsustainable tropical soils (Murgueitio *et al.*, 2011), compromising water storage capacity, nutrient cycling, biomass production, and biodiversity conservation (Safaei *et al.*, 2019). Soil structure and biological regulation allow for the characterization of soil health indicators, which are essential for establishing maintenance and recovery in eroded areas (Duran-Bautista *et al.*, 2020). Global soil loss is estimated at around 75 billion Mg each year, ranging from 13 to 40 Mg ha−1 year−1 in productive systems, causing economic losses of approximately USD 400 billion (GSP, 2017).

Colombia has 50.91 million hectares of land suitable for agricultural use, representing 4.6% of the country's total area. Of this, 45 million hectares are dedicated to livestock production and 4.9 million hectares to agricultural production; among the later, 60% are dedicated to permanent crops, 33% to temporary crops, and 7% to forest crops (Torres *et al.*, 2017). Livestock production occupies 30% of the area assigned to this activity, even through only 13.3% would be suitable for such use. In contrast, the agricultural sector uses only 4.7% of its potential area of 19.3% (Teutscherová *et al.*, 2021). This inbalance compromises soil quality and its capacity to provide ecosystem services. According to the IGAC, 15% of the country's soils are currently being overused, while 13% are underused. Colombian soil management is highly vulnerable to degradation due to biophysical conditions, forestry use, inadequate mechanization practices, the use of agrochemicals, and extensive livestock farming (Mora Marín *et al.*, 2017).

To addresed the unsustainable patterns of land use, various alternatives have been proposed that promote sustainable agricultural systems, conserve biodiversity, reduce greenhouse gas emissions, and diversify the income of local producers (De Beenhouwer *et al.*, 2013). Among these alternatives are tropical SAF establishments, which contribute to crop productivity and sustainability (Villa *et al.*, 2020). SAF provide ecosystem services such as climate change adaptation and mitigation (Schroth *et al.*, 2016), erosion management and soil quality improvement (Mortimer *et al.*, 2018), and carbon sequestration (Sharma *et al.*, 2016; N'Gbala *et al.*, 2017; Nadège *et al.*, 2019). The present study aims to analyze the contribution of SAF to soil conservation and their role in increasing in arthropod and vertebrate populations (Klein *et al.*, 2008; Tscharntke *et al.*, 2011), as well as in regulating water and nutrient dynamics (Niether *et al.*, 2020; Sauvadet *et al.*, 2020).

MATERIALS AND METHODS

The sources used to prepare this article were obtained from a review of databases such as Scopus, Science Direct, Springer Link, JSTOR, Web of Science, and Scielo. The search was conducted within an observation window between 1985 and 2021. To classify the articles in the databases on the selected topic, those published in categorized journals that met scientific standards and academic relevance were considered. Similarly, importance was given to research carried out in Colombia by different universities and institutions. The list of articles was generated using a combination of keywords in English (soil* or agroforestry), (Soil* or agroforestry *OR restoration), and (Soil* OR Remediation).

The selected publications were synthesized considering the background of agroforestry and ecosystem services, with a special focus on the stratified diversification of SAF in terms of their contribution to soil conservation or improvement. Based on the review of the articles, a matrix was constructed and recorded in a table, describing the most frequent positive impact of SAF that have been implemented by farmers; the contribution, based on the type of agroforestry structure and associated species, was highlighted. As a result of the review and analysis of the articles, the focus was on breaking down three fundamental topics that could be subjects of discussion in soil management: 1. Agroforestry and ecosystem services, 2. Benefits of SAF for maintaining soil fertility, and 3. Challenges of agroforestry systems for soil conservation.

RESULTS

General characteristics of agroforestry studies

Between 1985 and 2021, scientific output in agroforestry in Colombia increased significantly, reaching a total of 3,269 documents, produced by 159 institutions. The ten institutions with the largest contributions accounted for 2,233 publications, representing 68% of the total (Figure 1). Among them, the International Center for Tropical Agriculture (CIAT) (14.16%), the National University of Colombia (12.90%), and the National University of Colombia – Medellín Campus (8.9%) stand out.

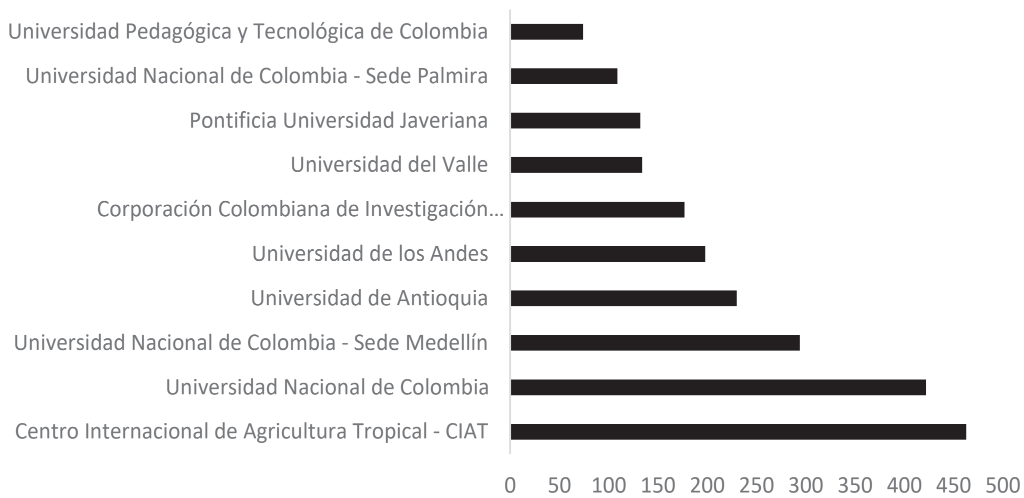


Figure 1. *Institutions with the highest academic output in agroforestry*

The areas of knowledge represented in the scientific production include 35.4% in biological sciences and agriculture, 15.33% in environmental sciences, 9.3% in earth and planetary sciences, 7.1% in engineering, 5.7% in biochemistry, genetics, and molecular biology, and 27.2% in other areas (Figure 2). The combination of these areas demonstrates that agroforestry research is a transdisciplinary science aligned with the study of ecosystem services.

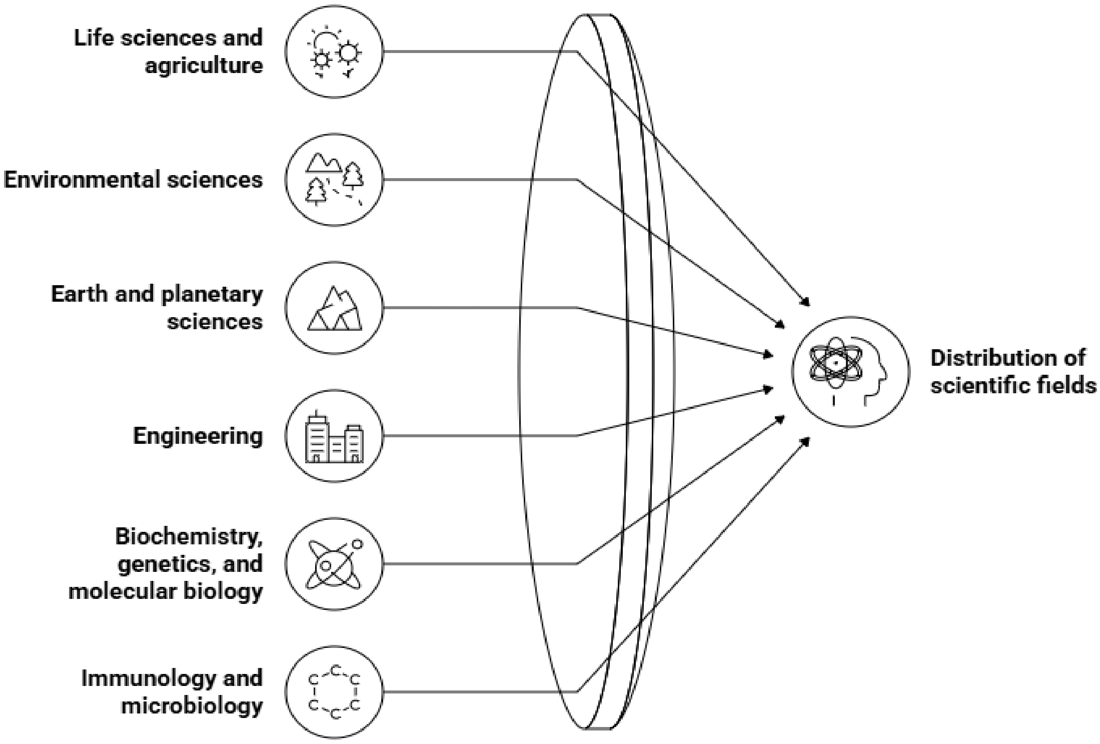


Figure 3. *Distribution of scientific fields in agroforestry systems*

Evidence on the role of agroforestry systems in providing ecosystem services

The bibliometric review showed that the establishment of agroforestry systems is widely recognized as an effective alternative for soil restoration and the generation of ecosystem services. These systems create structures that, in addition to providing productive services, promote nutrient fixation and increase soil fertility by integrating physical, chemical, and biological dimensions (Table 1).

Table 1. *Contribution of agroforestry systems to soil conservation.*

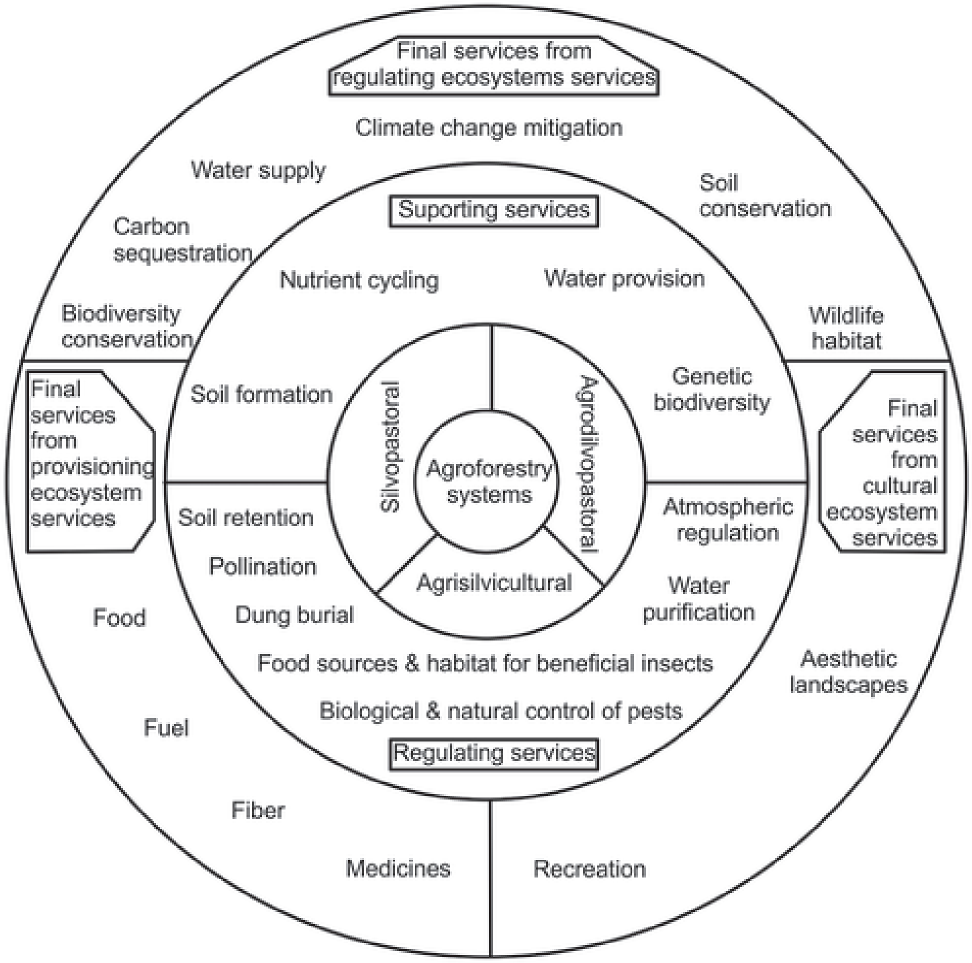
Agroforestry system	Description of SAF	Contribution to soil conservation	Authors	Country
Coffee agroforestry systems	Coffee cultivation associated with planted species such as Musaceae, palm trees, and leguminous trees, predominantly *Inga sp,* timber trees such as *Cedrela odorata* and *Mariosousa*.	In shaded coffee agroforestry systems (>50%), soil carbon storage can reach 90-145 Mg ha^{-1}, which is 15 times higher than in plantations with shade levels <30%.	Haggar *et al.* (2013); Jezeer *et al.* (2019).	Guatemala Perú
	Traditional coffee system associated with Inga sp, *Erythrina poeppigiana, Cordia alliodora, Musa sp.*, and *Persea americana* with shade levels of 42.86%.	In traditional low-density coffee systems, trees increased the amount of calcium (13.52 meq/100g) and magnesium (2.28 meq/100g) compared to intensive coffee systems with lower levels of calcium (5.48 meq/100g) and magnesium (1.24 meq/100g).	Valbuena-Calderón *et al.* (2017).	Colombia
Cacao agroforestry systems	Mixed crops of cacao (*Theobroma cacao* L.), banana (*Musa paradiasica* L.), and timber trees such as cedar (*Cedrelinga catenaeformis*).	A greater number of soil macrofauna (18 species) was found in mixed crops compared to the soil macrofauna (14 species) in secondary vegetation.	Duran-Bautista *et al.* (2020).	Colombia.
	Mixed crops consisting of cacao (*Theobroma cacao* L.), *Erythrina sp.*, and some *Ficus* species.	In this type of SAF, the soils had higher levels of K, P, Mg, Ca, and N.	De Oliveira Leite & Valle (1990).	Brasil.
	Cocoa crops associated with *Inga edulis, Ocotea longifolia, and Jacaranda Copaia* species, established on degraded pasture soils.	It was concluded that after establishing the SAF, soil quality improved by 42%.	Suarez *et al.* (2021).	Colombia.
	Coffee and cocoa crops associated with legumes such as *Erythrina poeppigiana* and timber trees such as *Cordia alliodora*.	In this type of SAF, soils had a higher amount of leaf litter and increased availability of N and K in the soil.	Beer *et al.* (1988).	Costa Rica.
	Mixed cultivation of cocoa associated with *Albizia adenocephala, Albizia guachapele, Albizia niopoides*, *Albizia plurijuga*, and *Albizia saman*.	This type of SAF showed a six-monthly leaf biomass production ranging from 3 to 10 t ha $^{-1}$, with N yields between 0.07 and 0.32 t ha $^{-1}$ for each regrowth, with an average release of C and N from the leaves of the six species of 31.0 and 32.0 days generated by pruning.	Anim-Kwapong (2003).	Africa Occidental.

Agroforestry system	Description of SAF	Contribution to soil conservation	Authors	Country
Silvopastoral Systems	One-year-old silvopastoral systems associated with timber trees as a soil recovery strategy compared to old pastures.	They harbor a greater number of macrofauna, especially termites, which are indicators of soil health, with an expected Jackknife specific richness of 11.6 and the presence of 8 species, compared to degraded pasture soils, where the presence of 4.9 species was reported.	Duran-Bautista *et al.* (2020).	Colombia.
	Silvopastoral systems composed of herbaceous plants such as *Brachiaria humidicola, Arachis pintoi*, and timber species such as *Gmelina arborea, Erythrina poeppigiana, Tectona grandis*, and *Cariniana pyriformis*.	The establishment of silvopastoral systems on grass-dominated soils led to a recovery in soil physical properties such as bulk density, with values of 1.09 g cm−3, and penetration resistance, with values of 3.77 MPa.	Polanía-Hincapié *et al.* (2021).	Colombia.
Agroforestry systems with tea	Tea crops associated with *Alnus nepalensis*.	Increases of 21 to 23% were recorded in microbial biomass of functional groups present in soils associated with *Alnus nepalensis*, with higher microbial biomass in Actinomycetes soil at 7.4 nmol g^{-1} of soil, compared to a Tea monoculture that presented values of 5.1 nmol g^{-1} of soil. Soil microbial biomass of bacteria increased to 67.0 nmol g^{-1} of soil compared to the Tea monoculture, with lower values of 51.3 nmol g^{-1} of soil.	Barrios *et al.* (2018).	suroeste de China.
Agroforestry systems with rubber	Cultivation of *Hevea brasiliensis* rubber trees and fruit trees.	Soil properties such as bulk density, total porosity, and soil penetrability were improved.	Rosas Patiño *et al.* (2016).	Colombia

DISCUSSION

Agroforestry and ecosystem services

Agroforestry, as a transdisciplinary science, is based on land-use systems in which woody plants interact biologically with crops and/or animals (Somarriba, 1998). Agroforestry systems (SAF) are classified according to their structure (nature and arrangement of components) and their function (uses and benefits) (Nair, 1985; Somarriba, 1998). To be recognized as an SAF, a system must meet certain conditions: it must include at least two plant species that interact biologically, one being a perennial woody species and another managed for agricultural and/or livestock purposes (Nair, 1985). The ecosystem services provided by SAF have generated significant interest for recognition under the Kyoto Protocol, due to their contribution to ecosystem conservation (Tscharntke *et al.*, 2011), biodiversity conservation (Palacios Bucheli & Bokelmann, 2017), food production for consumption and commercialization, which diversifies income and increases food security for farmers (Souza *et al.*, 2017; Jezeer *et al.*, 2019), as well as generating habitat for plant and animal species (Kay *et al.*, 2019) (Figure 1).



Note: Bateman *et al.* (2014); Swinton *et al.* **(2007); Zhang** *et al.* (2007) adapted from Palacios Bucheli and Bokelmann (2017).

Figure 1. *Ecosystem services in agroforestry systems*

SAF generate ecosystem services such as carbon storage, soil moisture conservation, and the conservation of plant species in dry tropical forests. They also provide secondary products such as wood, fruit, and fodder in livestock and agricultural systems, which can be used by farmers for various purposes and for the sale of products such as fruits and Musaceae (McNeely & Schroth, 2006; Tscharntke *et al.*, 2011). They are considered an ecological restoration alternative to mitigate the effects of climate change, reduce the impacts of soil degradation, and contribute to lowering CO2 concentrations (Beer *et al.* 2003; Vásquez & Arellano 2012; Bertomeu García *et al.* 2019; Abbas *et al.* 2017).

Relationship between agroforestry systems and soil chemical properties

Soil conservation in SAF is associated with the presence of nitrogen-fixing trees or trees with deep root systems, which enhance nutrient availability through biological fixation, nutrient recycling, and organic matter accumulation (Jezeer *et al.*, 2019). The diversification of shade trees improves soil fertility, helps control weeds, and reduces the use of agricultural inputs such as herbicides, fertilizers, and pesticides (Vaast *et al.*, 2006; Tscharntke *et al.*, 2011).

A direct contribution of shade tree diversification in SAF is the incorporation of organic matter through biomass and leaf litter. It has been reported that leguminous tree species can provide between 5,000 and 10,000 kg of organic matter per hectare per year (Beer, 1988). Trees can accelerate the accumulation of N, P, and K. For example, *Erythrina poeppigiana* is used by farmers to contribute nitrogen to the soil and provide other ecosystem services, such as supplying wood and fodder for animal feed. It has an annual nutrient return through leaf litter of 90 to 100 percent of the nutrient storage of the above-ground biomass (Beer, 1988) and is well adapted to the climatic conditions of the tropical dry forest (Ordoñez & Rangel-CH, 2020).

Other species associated with SAF, such as *Cestrum ochraceum*, *Viburnum triphyllum*, and *Alnus jorullensis*, improve N fixation, reduce soil desertification, and facilitate carbon sequestration (Hajjar *et al.*, 2008; Palacios Bucheli & Bokelmann, 2017). In some Peruvian territories, it has been found that species associated with SAF, such as *Dodonea viscosa*, may be related to an increase in organic matter and soil pH. Meanwhile, the presence of *Schinus molle* in SAF can have positive effects on nitrogen and phosphorus content, moisture, and soil respiration (Bolaños Angulo *et al.*, 2014).

The benefits of SAF on soil chemical properties depend on the design and agronomic management of the system. In other words, if traditional agronomic practices are maintained, it may not be possible to achieve a balance between productivity and the expected benefits, as described in previous research. However, further studies are needed to understand how soil fertility can be improved not only through the effects of shade trees but also through the overall implementation and management of agroforestry systems. Another important area of investigation is soil quality in SAF, which encompasses key characteristics such as physical and biological properties and the formation of soil aggregates (Velásquez *et al.*, 2007).

Changes in the physical properties of the soil are related to anthropogenic activities, the microclimate, and the characteristics of the tree species established in SAF or found naturally. Designing SAF in arrangements such as alleys, fallow fields with trees, grass strips, crop rotation, or permanent crops has been shown to have benefits for some soil properties, such as reduced runoff, increased infiltration, protection of the soil from adverse insolation, and reduced evaporation (Siebert, 2002; Tscharntke *et al.*, 2011). In Colombia, there is still a lack of information on the long-term effect of SAF on physical soil properties such as bulk density, porosity, soil moisture, and aggregate stability, but progress continues to be made in this field of research of interest to the agricultural sector. For example, Suarez *et al.* (2021) found a relationship between a higher proportion of biogenic macroaggregates in soils and forestry practices, which in turn enhances the soil water cycle by improving properties such as bulk density, penetration resistance, and porosity.

Several studies have been conducted to investigate the relationship between SAF and soil physical properties. Authors such as Stocker *et al.* (2020) studied SAF with timber and fruit trees in Brazil and concluded that physical properties such as bulk density and total porosity were the most sensitive to change. They also observed that the intensity of root development is a key factor in promoting soil physical quality and can therefore lead to changes in physical properties in the short term. Meanwhile, authors such as Cherubin *et al.* 2019 studied SAF and their relationship with the physical properties of soil in the Colombian Amazon and observed that the most significant changes were evident in the topsoil, which had a high abundance of roots mixed with a soft layer composed mainly of porous and rounded aggregates.

Some variables, such as the age of the SAF and soil depth, influence the effect of SAF on soil physical properties. Arévalo-Gardini *et al.* (2015) investigated this relationship in SAF with cocoa in the Amazon region of Peru and concluded that the aforementioned variables have significant effects on physical indicators such as bulk density, porosity, and field capacity.

While several studies show positive impacts of SAF on soil physical properties, authors such as Souza *et al.* (2017) found that a SAF of coffee associated with banana and ingá did not alter the physical attributes of the soil evaluated: bulk density, macroporosity, microporosity, and total porosity in relation to conventional coffee cultivation. Other research conducted on SAF associated with Australian cedar, teak, and African mahogany showed that they did not influence the physical attributes of the soil (Jácome *et al.*, 2020).

Challenges of agroforestry systems in soil conservation

The challenge of establishing and designing SAF must be determined by the level of shade, tree diversification, and precise knowledge of: The selection of trees adapted to the zones of life, soil properties (physical, chemical, biological), agroclimatic conditions (sunlight, radiation, temperature, and relative humidity), and agroforestry design, which must correspond to the objectives of the producers and the purpose of establishment (Van Der Wolf *et al.* 2019; De Sousa *et al.* 2019). Although a SAF cannot replace the forest when it comes to tropical biodiversity (Gibson *et al.* 2011; Suárez *et al.* 2018), it can contribute to the diversity of soil macrofauna and improve its physical and chemical properties, which contribute to the sustainability of the soil and production systems (Piza *et al.* 2021).

Studies conducted by Basto *et al.* (2015) in areas of tropical dry forest (Tataco desert) in the department of Huila, Colombia, show that species such as *Gliricidia sepium* (Matarraton), *Pithecellobium dulce* (Payandé), *Cordia dentata* (Gomo), *Acacia canescens* (Ambuco), *Guazuma ulmifolia* (Guácimo), *Erythrina poeppigiana* (Cachimbo), and *Leucaena leucocephala* (Leucaena) are recommended for use in silvopastoral systems because of their adaptation to high temperatures due to their morphology, as they are a source of animal feed and provide ecosystem services for soil protection and conservation.

In turn, in other agroforestry arrangements, soil health has increased positively through the accumulation of leaf litter, which favors soil biology due to the food and microhabitat that develops in it (Rosas Patiño *et al.* 2016; Korboulewsky *et al.* 2016). It has been found in SAF soils with *Alnus glutinosa* that a higher biomass of this species increases the population of Actinomycetes and gram-positive and gram-negative bacteria (Golinska & Dahm, 2011; Snajdr *et al.*, 2013); similar reports have been recorded in soils in the Colombian Amazon with the presence of the Paricá species (*Schizolobium amazonicum* Huber), where it presented a richness of 13 taxa associated with SAF (Duran-Bautista *et al.*, 2020).

Finally, it is important to note that the soil recovery mechanism depends on both the health of the soil and the management practices of the production systems. Moreover, if the objective is to conserve the soil independently of the crop, it is essential to evaluate the physical, chemical, and biological characteristics to guide and select tree species, bioenergy techniques, and management practices according to what is intended to be conserved or improved in the soil.

CONCLUSIONS

Agroforestry through SAF generates ecosystem services for soil conservation, such as carbon storage and nutrient availability, and increases leaf litter, which contributes to the richness of macrofauna and the availability of nutrients such as N, K, P, Mg, and Ca. These benefits are related to the structure of the SAF, i.e., the diversity of tree species implemented, the type of agroforestry systems, and soil management conditions. It is possible that developing practices to improve soil fertility must be related to the objectives of producers, the scale of production systems, and the specific biophysical conditions of each area.

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CONFLICT OF INTEREST

The manuscript was prepared and reviewed with the participation of all authors, who declare that there is no conflict of interest that could compromise the validity of the results presented.

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