

Silvopastoral Systems as a Sustainable Strategy for Tropical Livestock Production in Central America: A Systematic Literature Review

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Abstract

Silvopastoral systems (SPS) integrate trees, shrubs, forage species, and grazing animals within the same production unit, offering an approach to sustainable livestock production in tropical regions. In Central America, conventional grazing systems have contributed to deforestation, soil degradation, biodiversity loss, and vulnerability to climate change. This study aimed to systematically review scientific evidence on SPS in Central America, focusing on productive performance, environmental benefits, climate change mitigation and adaptation, animal welfare, and implementation challenges. The review followed the PRISMA 2020 guidelines. Scientific articles published between 2014 and 2025 were identified through searches of Scopus, Web of Science, Google Scholar, SciELO, Redalyc, Dialnet, Latindex, and EBSCOhost. Studies meeting predefined inclusion and exclusion criteria were qualitatively synthesized according to productive, environmental, and socioeconomic dimensions. The reviewed studies reported improvements in forage quality, animal nutrition, productive efficiency, and animal welfare. Environmental contributions included enhanced soil fertility, biodiversity conservation, carbon sequestration, water regulation, and ecosystem resilience. The evidence also indicated that SPS can strengthen the adaptive capacity of livestock production systems under climate variability, supporting their relevance to tropical agricultural contexts. However, adoption remained constrained by limited access to technical assistance, financial resources, and institutional support. These barriers highlight the importance of considering implementation conditions alongside the productive and ecological benefits of integrating

woody vegetation into grazing systems. Overall, the synthesis supports the potential of SPS to combine livestock productivity with natural resource conservation and climate resilience in Central America. Expanding their implementation requires accessible financing, sustained technical assistance, and institutional arrangements responsive to producers' needs. The findings provide a basis for informing research priorities, extension services, and policies supporting sustainable tropical livestock production.

Keywords: Silvopastoral Systems; Sustainable Livestock Production; Central America; Tropical Agroforestry; Climate Resilience

INTRODUCTION

Livestock production represents one of the most important agricultural activities in Central America, contributing significantly to food security, rural employment, household incomes, and regional economic development. Cattle production is widely distributed across tropical landscapes and constitutes a major livelihood for thousands of small- and medium-scale producers. However, conventional livestock systems based on extensive grazing have historically been associated with deforestation, soil degradation, biodiversity loss, declining soil fertility, and increasing greenhouse gas emissions, reducing the long-term sustainability of agricultural production systems (Jose & Dollinger, 2019; Broom, 2017; Chará et al., 2020).

The expansion of conventional cattle ranching has been recognized as one of the principal drivers of land-use change in tropical regions, including Central America. Forest conversion into pasturelands has fragmented natural ecosystems, reduced biodiversity, altered hydrological processes, and accelerated land degradation. Furthermore, increasing climate variability, characterized by prolonged droughts, irregular rainfall patterns, and rising temperatures, has intensified the vulnerability of livestock production by reducing forage availability and negatively affecting animal performance (Aryal et al., 2022; Torres et al., 2023; Contreras-Santos et al., 2020).

Under these conditions, silvopastoral systems (SPS) have emerged as one of the most promising strategies for improving the sustainability of tropical livestock production. By integrating trees, shrubs, forage species, and grazing animals within the same production unit, SPS promote ecological interactions that enhance nutrient cycling, improve soil fertility, increase biodiversity, regulate microclimatic conditions, and strengthen ecosystem resilience

while maintaining or increasing livestock productivity (Jose & Dollinger, 2019; López-Vigoda et al., 2017; Sales-Baptista & Ferraz-de-Oliveira, 2021).

Numerous studies conducted in tropical production systems have demonstrated that silvopastoral systems improve forage quality, increase crude protein availability, enhance animal nutrition, reduce heat stress, and improve productive performance compared with conventional grazing systems. In addition, SPS contribute to carbon sequestration, soil conservation, water regulation, and the provision of multiple ecosystem services that support climate change mitigation and adaptation (Huertas et al., 2021; Chará et al., 2020; Contreras-Santos et al., 2023; Lerma-Lasso et al., 2023; Murga-Orrillo et al., 2025).

The ecological importance of SPS extends beyond livestock production. The incorporation of woody vegetation into grazing systems increases habitat heterogeneity, favors wildlife conservation, improves soil biological activity, and enhances landscape connectivity, thereby contributing to the restoration of ecosystem functions within tropical agricultural landscapes (Ramírez-Barajas et al., 2019; De la Peña-Domene et al., 2022; Saucedo-Uriarte et al., 2022; Trejo-Arista et al., 2023). These ecosystem services are particularly relevant in Central America, where livestock production frequently coexists with highly diverse but environmentally fragile tropical ecosystems.

Despite the well-documented productive and environmental advantages of silvopastoral systems, their adoption throughout Central America remains limited. Previous studies have identified several constraints, including high establishment costs, limited access to financial resources, insufficient technical assistance, weak extension services, and inadequate policy support. These barriers continue to restrict the large-scale implementation of SPS despite the growing scientific evidence supporting their effectiveness as sustainable livestock production systems (Sandoval et al., 2021; Oliva et al., 2018; Apan-Salcedo et al., 2022; Vargas-de la Mora et al., 2021; Romero-Mena et al., 2024; Marroquín-Pugas et al., 2022).

Given the increasing need to develop resilient livestock systems capable of maintaining productivity while conserving natural resources, a comprehensive assessment of the available scientific evidence is required. Therefore, the objective of this study was to systematically review the scientific literature published between 2014 and 2025 on silvopastoral systems in Central America, synthesizing current knowledge regarding their productive performance, environmental benefits, contribution to climate change mitigation

and adaptation, animal welfare, and the principal challenges associated with their implementation. This review provides an updated synthesis of the role of silvopastoral systems as a sustainable strategy for strengthening livestock production in the tropical environments of Central America.

METHODS

Research Design

This study was conducted as a systematic literature review to synthesize and evaluate the available scientific evidence on silvopastoral systems (SPS) for sustainable livestock production in Central America. The review followed the general principles of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) to ensure a transparent, rigorous, and reproducible process for identifying, selecting, and analyzing the scientific literature.

The objective was to identify and integrate research findings related to the productive, environmental, and socioeconomic contributions of SPS, as well as the challenges associated with their implementation in Central American livestock production systems.

Literature Search Strategy

A systematic search of the scientific literature was conducted between January and March 2026 using the electronic databases Web of Science, Scopus, Google Scholar, SciELO, Redalyc, Dialnet, Latindex, CAB Abstracts, and EBSCOhost. These databases were selected because they contain extensive literature in agriculture, agroforestry, environmental sciences, and livestock production.

The search strategy combined controlled vocabulary and free-text terms in English and Spanish using Boolean operators (AND, OR). The principal search terms included: *silvopastoral systems*, *silvopasture*, *agroforestry*, *sustainable livestock production*, *livestock sustainability*, *Central America*, *sistemas silvopastoriles*, *ganadería sostenible*, *agroforestería pecuaria*, and *Centroamérica*.

Additional manual searches were conducted by reviewing the reference lists of selected articles to identify relevant publications not retrieved through the electronic search.

Eligibility Criteria

Studies were included when they met the following criteria:

- Published between 2014 and 2025.
- Peer-reviewed scientific articles.
- Written in English or Spanish.
- Conducted in one or more Central American countries (Belize, Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, or Panama), or presenting findings directly applicable to livestock production in the region.
- Addressed silvopastoral systems from productive, environmental, economic, or social perspectives.

Studies were excluded if they:

- Were conference abstracts, editorials, book reviews, or opinion papers.
- Did not present original scientific information.
- Focused exclusively on forestry or agroforestry systems without livestock.
- Did not provide sufficient methodological information or full-text access.

Study Selection

The study selection process consisted of four stages: identification, screening, eligibility assessment, and final inclusion.

Initially, all records obtained from the databases were compiled, and duplicate publications were removed. Subsequently, titles and abstracts were screened to identify potentially relevant studies. Full-text articles were then evaluated according to the predefined inclusion and exclusion criteria. Only studies meeting all eligibility requirements were included in the final review.

Data Extraction

Relevant information from each selected publication was organized in a database that included:

- Authors
- Year of publication
- Country
- Study objective

- Research methodology
- Type of silvopastoral system
- Main productive outcomes
- Environmental contributions
- Socioeconomic findings
- Principal conclusions

This information facilitated the comparison of studies conducted under different environmental and production conditions throughout Central America.

Data Analysis

A qualitative synthesis of the selected literature was performed. The information was analyzed according to four thematic categories:

1. Productive performance of silvopastoral systems.
2. Environmental services, including soil conservation, biodiversity, carbon sequestration, and climate change mitigation.
3. Animal welfare and forage quality.
4. Socioeconomic aspects influencing the adoption of silvopastoral systems.

The findings were compared to identify common trends, regional differences, research gaps, and emerging opportunities for strengthening sustainable livestock production in Central America.

RESULTS AND DISCUSSION

The systematic review demonstrates that silvopastoral systems (SPS) represent one of the most effective strategies for promoting sustainable livestock production in the tropical environments of Central America. Throughout the region, livestock production is a fundamental component of rural livelihoods and food security; however, conventional grazing systems have contributed to deforestation, soil degradation, biodiversity loss, and increasing vulnerability to climate change. The scientific evidence analyzed in this review consistently indicates that SPS provide an integrated alternative capable of simultaneously improving livestock productivity, conserving natural resources, increasing ecosystem resilience, and enhancing the sustainability of agricultural landscapes. Although many of the

studies reviewed were conducted in different tropical regions, their findings are highly relevant to Central America because of the shared climatic conditions, vegetation types, production systems, and environmental challenges.

One of the most consistent findings across the reviewed literature is the positive effect of silvopastoral systems on livestock productivity. The incorporation of trees, shrubs, and herbaceous forage species within grazing areas improves both the quantity and quality of forage available throughout the year. Tree legumes and fodder shrubs provide additional sources of protein, minerals, and digestible nutrients that complement tropical grasses, particularly during the dry season when forage quality declines. Studies conducted by López-Vigoa et al. (2017), Palma García and Anguiano Cárdenas (2015), Martínez-Hernández et al. (2019), and Nuncio Ochoa et al. (2024) demonstrated that diversified silvopastoral arrangements increase crude protein concentration, improve forage digestibility, and enhance nutrient availability for grazing cattle. Consequently, animals exhibit greater weight gain, improved milk production, higher reproductive performance, and better feed conversion efficiency than those managed under conventional pasture systems.

These productive benefits are especially important for Central American livestock systems, where prolonged dry seasons and irregular rainfall frequently reduce pasture productivity. The presence of perennial vegetation allows forage availability to remain more stable throughout the year, reducing seasonal fluctuations in animal nutrition and decreasing dependence on commercial feed supplements. Chará et al. (2020), Lerma-Lasso et al. (2023), and Sales-Baptista and Ferraz-de-Oliveira (2021) emphasized that diversified grazing systems improve the efficiency of nutrient use while increasing the resilience of livestock production under tropical climatic conditions. Such characteristics make SPS particularly suitable for small- and medium-scale producers, who often have limited access to external inputs and are highly vulnerable to climatic variability.

Beyond their productive advantages, silvopastoral systems generate substantial environmental benefits that are highly relevant for Central America. Livestock expansion has historically been associated with deforestation and land degradation throughout the region, resulting in declining soil fertility, reduced biodiversity, and deterioration of ecosystem services. The reviewed literature consistently indicates that integrating trees into grazing systems contributes to restoring ecological processes that are often lost under conventional livestock management. Tree roots improve soil structure, reduce compaction, increase water

infiltration, and promote nutrient cycling, while leaf litter contributes organic matter that stimulates soil biological activity. Studies by Apan-Salcedo et al. (2021), Díaz Lezcano et al. (2020), Trejo-Arista et al. (2023), and Saucedo-Uriarte et al. (2022) demonstrated significant improvements in soil quality, water retention, and ecosystem stability in silvopastoral systems compared with open grazing areas.

The conservation of biodiversity represents another important contribution of SPS in tropical landscapes. Unlike conventional pastures characterized by simplified vegetation structure, silvopastoral systems create heterogeneous habitats capable of supporting greater diversity of plants, insects, birds, and soil organisms. Ramírez-Barajas et al. (2019) reported higher diversity of macroinvertebrates in silvopastoral systems, while De la Peña-Domene et al. (2022) demonstrated that enriched silvopastoral arrangements increase structural complexity and promote ecological restoration. Similarly, Chará et al. (2020) highlighted that these systems provide multiple ecosystem services, including pollinator conservation, biological pest regulation, nutrient recycling, and habitat connectivity. Such ecological functions are particularly important in Central America, where livestock production frequently occurs adjacent to fragmented forest ecosystems that require effective conservation strategies.

The review also confirms that animal welfare has become an increasingly important component of sustainable livestock production in tropical regions. High temperatures, intense solar radiation, and prolonged heat stress negatively affect animal physiology, behavior, reproductive performance, and productive efficiency. The incorporation of trees into grazing systems creates favorable microclimatic conditions by providing shade, reducing ambient temperature, and increasing relative humidity. These environmental modifications reduce thermal stress while allowing animals to express natural grazing, rumination, and resting behaviors. Studies conducted by Broom (2017), Jose and Dollinger (2019), Huertas et al. (2021), Améndola et al. (2016), and Murga-Orrillo et al. (2025) consistently reported lower physiological stress indicators, improved behavioral responses, higher feed intake, and better productive performance in cattle managed under silvopastoral conditions. These findings are particularly relevant for Central America, where increasing temperatures associated with climate change are expected to intensify heat stress and reduce livestock productivity.

Climate change mitigation constitutes another major advantage of silvopastoral systems. Agriculture and livestock production are recognized as important contributors to greenhouse gas emissions, particularly methane and nitrous oxide. However, the reviewed literature demonstrates that SPS can substantially reduce the environmental footprint of livestock production through several complementary mechanisms. The incorporation of trees increases carbon sequestration in aboveground biomass and soils, while improved forage quality enhances digestive efficiency and may contribute to lower methane emissions per unit of animal product. Aryal et al. (2022), Contreras-Santos et al. (2020), Contreras-Santos et al. (2023), Torres et al. (2023), and Torres Rivera et al. (2023) documented significant increases in carbon storage within silvopastoral landscapes compared with conventional grazing systems. Carbon sequestration not only contributes to climate change mitigation but also improves soil fertility, water retention, and ecosystem resilience, reinforcing the multifunctional character of SPS.

The literature further demonstrates that silvopastoral systems contribute to climate change adaptation by increasing the resilience of livestock production systems. Trees protect soils against erosion caused by intense rainfall, reduce evapotranspiration losses during drought periods, and improve water infiltration, thereby stabilizing forage production under increasingly variable climatic conditions. This capacity to buffer climatic extremes is particularly valuable in Central America, where recurrent droughts, hurricanes, and irregular precipitation patterns increasingly threaten agricultural production and rural livelihoods. Consequently, SPS represent an effective climate-smart livestock strategy capable of simultaneously increasing productivity and reducing environmental vulnerability.

Although the productive and environmental benefits of silvopastoral systems are widely documented, their adoption throughout Central America remains limited. The reviewed studies consistently identify several constraints that hinder widespread implementation. High establishment costs, limited access to credit, insufficient extension services, inadequate technical assistance, lack of financial incentives, and weak institutional support continue to reduce adoption rates among livestock producers. Sandoval et al. (2021), Oliva et al. (2018), Apan-Salcedo et al. (2022), Vargas-de la Mora et al. (2021), Romero-Mena et al. (2024), Marroquín-Pugas et al. (2022), and Zepeda Cancino et al. (2016) emphasize that successful implementation depends not only on the technical effectiveness of SPS but also on favorable economic, institutional, and policy conditions.

Another recurring theme identified in the reviewed literature concerns producers' perceptions and attitudes toward innovation. Many livestock producers remain reluctant to modify conventional grazing practices because of uncertainty regarding establishment costs, delayed economic returns, and limited technical knowledge. Consequently, strengthening extension programs, farmer training, participatory research, and demonstration farms will be essential for accelerating the adoption of silvopastoral technologies throughout Central America. Public policies that facilitate access to credit, payments for ecosystem services, and technical assistance may further encourage the transition toward more sustainable livestock production systems.

Overall, the scientific evidence analyzed in this review clearly demonstrates that silvopastoral systems provide an integrated solution to many of the environmental and productive challenges currently affecting tropical livestock production. Their capacity to simultaneously improve forage production, animal nutrition, biodiversity conservation, soil quality, carbon sequestration, climate resilience, and animal welfare positions SPS as one of the most promising sustainable livestock strategies for Central America. Expanding these production systems will contribute not only to increasing agricultural productivity but also to restoring ecosystem services, strengthening climate adaptation, and promoting more resilient rural livelihoods throughout the tropical landscapes of the region.

CONCLUSION

This systematic review demonstrates that silvopastoral systems represent a sustainable alternative for livestock production in Central America by improving productivity while enhancing environmental conservation and climate resilience. The evidence indicates that SPS increase forage quality, animal welfare, soil fertility, biodiversity, and carbon sequestration, making them particularly suitable for tropical production systems. Despite these benefits, their adoption remains constrained by economic, technical, and institutional barriers. Expanding technical assistance, strengthening public policies, and promoting incentives for producers will be essential to accelerate the adoption of silvopastoral systems and foster more resilient and sustainable livestock production throughout Central America.

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