PAB Pesquisa Agropecuária Brasileira 60 years

COP30
Animal Science/ Review

jornada pelo CLIMA #TemQueTerCiência

ISSN 1678-3921

Journal homepage: www.embrapa.br/pab

For manuscript submission and journal contents, access: www.scielo.br/pab

Biodiverse and multifunctional silvopastoral system and its contribution to climate change mitigation

Abstract – The objective of this work was to synthesize the functional contributions of a biodiverse silvopastoral system to climate regulation. Through the lenses of ecological intensification and regenerative agriculture, data obtained over a decade by key studies monitoring a biodiverse silvopastoral system in the municipality of São Carlos, in the state of São Paulo, Brazil, were analyzed and evaluated. This approach allowed observing the transition from an input-dependent model to a system based on process management. In addition to mitigating climate change, this system serves as a multifunctional engine. Specifically, it reduces horn fly infestations by 38% due to an enhanced dung beetle activity, optimizes hydrological resilience through a deep-water pump mechanism, and reduces wildfire risks. Despite the gaps in silvocultural protocols for native timber, the studied biodiverse silvopastoral system indicates that managing functional diversity is essential for optimizing ecosystem services. The integration of functional groups, such as nitrogen fixers and deep-rooted native trees, allows a high animal productivity due to ecosystem restoration, contributing to climate change mitigation. The inclusion of leguminous species is the main driver for a significant increase in deep-soil carbon in the mineral-associated organic matter fraction, as well as for a decrease in methane emissions.

Index terms: carbon sequestration, ecological intensification, ecosystem services, mineral-associated organic matter, regenerative agriculture.

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Received
May 05, 2025

Accepted
May 05, 2026

How to cite
SANTOS, S.A.; NICODEMO, M.L.F.; PEZZOPANE, J.R.M.; BERNARDI, A.C. de C.; MOURA, L.F. Biodiverse and multifunctional silvopastoral system and its contribution to climate change mitigation. **Pesquisa Agropecuária Brasileira**, v.61, e04413, 2026. DOI: https://doi.org/10.1590/S1678-3921.pab2026.v61.04413.

Sistema silvipastoral biodiverso multifuncional e sua contribuição na mitigação de mudanças climáticas

Resumo – O objetivo deste trabalho foi sintetizar as contribuições funcionais de um sistema silvipastoril biodiverso na regulação climática. Sob as lentes da intensificação ecológica e da agricultura regenerativa, foram analisados e avaliados dados obtidos durante mais de uma década por estudos chave de monitoramento de sistema silvopastoril biodiverso no município de São Carlos, no estado de São Paulo, Brasil. Esta abordagem permitiu observar a transição de um modelo dependente de insumos para um sistema baseado na gestão de processos. Além de mitigar mudanças climáticas, este sistema age como motor multifuncional. Especificamente, promove mecanismos de regulação ecológica que reduzem as infestações por mosca-dos-chifres em 38% devido ao aumento da atividade dos besouros coprófagos, otimiza a resiliência hidrológica por meio de mecanismo de bomba d'água profunda e reduz riscos de incêndios florestais. Apesar das lacunas nos protocolos silviculturais para

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madeira nativa, o sistema silvipastoril biodiverso indica que o manejo da diversidade funcional é essencial para otimizar serviços ecossistêmicos. A integração de grupos funcionais, como fixadores de nitrogênio e árvores nativas de raízes profundas, permite alta produtividade animal devido à restauração de ecossistemas, colaborando com a mitigação de mudanças climáticas. A inclusão de espécies leguminosas é o principal fator para aumento significativo do carbono na fração de matéria orgânica associada a minerais em solo profundo, bem como para redução das emissões de metano.

Termos para indexação: sequestro de carbono, intensificação ecológica, serviços ecossistêmicos, matéria orgânica associada a minerais, agricultura regenerativa.

Introduction

Pasture-based livestock systems have long dominated the Brazilian agricultural landscape, occupying vast areas of land with a consequently limited ecological function (Bolfe et al., 2024). While these systems have historically supported large-scale meat and milk production, they are increasingly criticized for contributing to deforestation, greenhouse gas emissions, soil degradation, and biodiversity loss (Adams et al., 2021).

In response to the urgent need for sustainable land-use strategies, silvopastoral systems have emerged as a primary pathway for ecological intensification (Jose et al., 2019; Veloso et al., 2020). When designed with a high functional biodiversity, these systems align with the principles of regenerative agriculture, by shifting from an input-dependent model toward process management, enabling the active restoration of soil health, deep-soil carbon sequestration, and ecosystem resilience (Newton et al., 2020). According to the concept of agricultural multifunctionality developed in the 1990s, such diversity optimizes ecosystem resilience, supports natural nutrient cycling, and improves soil structure and fertility (Caron et al., 2008). This underscores the importance of evaluating biodiverse silvopastoral systems, particularly those incorporating species that provide non-timber forest products (Bento et al., 2020).

Focusing on biodiversity and multifunctionality, silvopastoral systems also promote an efficient land use, yielding a wide range of environmental and productive benefits (Sales-Baptista & Ferraz-de-Oliveira, 2021). The inclusion of woody components, for example, enhances above- and belowground carbon stocks, contributing significantly to greenhouse gas mitigation (Aryal et al., 2022). This potential is further amplified by the strategic integration of leguminous species, which optimize nitrogen cycling and facilitate the stabilization of organic matter in deeper soil layers, providing a suite of other ecosystem services essential for system resilience (Lustosa Filho et al., 2024).

From an animal production perspective, silvopastoral systems can improve microclimatic conditions, enhancing animal welfare and productivity (Lemes et al., 2021), while reducing methane emissions per unit of output (Brunetti et al., 2025). These systems can also provide a variety of ecosystem services, including biodiversity conservation, water regulation, fire control, and habitat provision (Carvalho et al., 2024).

Given the aforementioned benefits, silvopastoral systems represent a key route to ecological intensification, establishing the foundation for an improved production efficiency (Jose et al., 2019; Kremen, 2020; Veloso et al., 2020). Such approach fulfills the increasing demand for nature-based solutions that actively restore ecosystem functions (Kremen, 2020; Kaushal et al., 2025). In this sense, biodiverse silvopastoral systems embody the principles of regenerative agriculture, prioritizing process management (Newton et al., 2020). These models conform with international frameworks, such as Sustainable Development Goals 2 (Zero Hunger), 13 (Climate Action), and 15 (Life on Land) of the United Nations, specifically Target 2.4 for a resilient food production (Chará et al., 2019).

In Brazil, silvopastoral systems are a strategic alternative to monoculture pastures as they enhance production efficiency and provide ecosystem services (Agethen et al., 2024). However, approximately 50% of the silvopastoral systems in the country consist of only a single, often exotic, tree species; the exception is the Northern region, where a higher tree diversity is more common (Bento et al., 2020). By moving beyond simple species richness toward the management of a functional process, these systems offer a scalable pathway for reconciling agricultural yields with an active environmental restoration. In this scenario, further researches are needed to fill the critical gap regarding the multifunctional potential of systems

that integrate native trees with legume-intercropped pastures.

The objective of this work was to synthesize the functional contributions of a biodiverse silvopastoral system to climate regulation.

Materials and Methods

This study is a systematic review and structured synthesis of secondary data obtained from researches on a long-term experimental biodiverse silvopastoral system established in 2008 by Nicodemo et al. (2016) in the municipality of São Carlos, in the state of São Paulo, Brazil (21º57'S, 47º50'W, at 860 m above sea level). Given the system's high structural and functional complexity, longitudinal data were used to evaluate spatial and temporal interactions between trees, multi-species pastures, and livestock, following the framework proposed by Foo et al. (2021).

The criteria for the inclusion of the sourced works were: peer-reviewed scientific articles, research conducted specifically at the biodiverse silvopastoral system in the municipality of São Carlos, and studies addressing at least one of the core domains (carbon dynamics, methane emissions, or multifunctional ecosystem services). A total of 26 peer-reviewed works support the analytical framework. Of these, seven studies published between 2015 and 2023 form the core database for the synthesis (Table 1), while 19 other relevant works on silvopastoral systems complement the discussion.

The selected studies were categorized into two primary domains: carbon sequestration and methane emissions, and multifunctionality and associated ecosystem services. A narrative synthesis approach was used to identify key patterns and research gaps, interpreting the empirical data from the biodiverse silvopastoral system within the context of low-input and self-sufficient agricultural strategies. When data permitted, the biodiverse silvopastoral system was compared with conventional pasture systems to assess its relative benefits regarding climate regulation and system autonomy.

The analysis of the biodiverse silvopastoral system was conducted through the lenses of the principles of ecological intensification (Dumont et al., 2013; Kremen, 2020) and regenerative agriculture (Newton et al., 2020). This framework allowed evaluating the transition from an input-dependent model toward process management. The system's capacity for self-regulation and restoration was analyzed based on four regenerative pillars: soil health and carbon stabilization, measured via mineral-associated organic matter (MAOM) fractions and deep-soil carbon deposition (Lustosa Filho et al., 2024); biological regulation, driven by the suppression of pests and the role of functional biodiversity (Oliveira et al., 2017); hydrological resilience, assessed through water-use efficiency, the deep-water pump mechanism, and niche complementarity (Pezzopane et al., 2015; Nicodemo & Primavesi, 2019); and system autonomy, focused on the substitution of external chemical inputs by internal biological processes and nitrogen fixation (Dumont et al., 2013).

The authors benefited from the assistance of Gemini (Google, Mountain View, CA, USA) for language refinement and structural organization of the manuscript. However, all data analysis, scientific interpretation, and conclusions remain the sole responsibility of the authors.

Table 1. Peer-reviewed studies conducted at the evaluated biodiverse silvopastoral system, located in the municipality of São Carlos, in the state of São Paulo, Brazil.

Study	Focus area/service	Domain
Furtado et al. (2023)	Methane emission	Carbon sequestration & methane emissions
Lemes et al. (2021)	Animal welfare	Multifunctionality & ecosystem services
Marcondelli (2019)	Nutrient cycling/litterfall	Multifunctionality & ecosystem services
Nicodemo et al. (2016)	Tree management and pruning	Multifunctionality & ecosystem services
Oliveira et al. (2017)	Biological pest control	Multifunctionality & ecosystem services
Pezzopane et al. (2015)	Microclimate and shading	Multifunctionality & ecosystem services
Pezzopane et al. (2019)	Microclimate buffering	Multifunctionality & ecosystem services

Carbon sequestration and methane emissions in silvopastoral systems

Forest management and structure significantly influence carbon reservoirs and fluxes within integrated ecosystems. In silvopastoral systems worldwide, soil carbon sequestration or loss rates vary widely, ranging from -0.72 to 2.2 Mg ha^{-1} per year, depending on climate, soil conditions, and management practices (Fungo et al., 2021). This variability underscores the importance of regulating environmental fluxes to the atmosphere using optimized system designs (Dumont et al., 2013).

To effectively transform integrated systems into a robust carbon sink, management practices should prioritize internal nutrient return (Madari et al., 2024). In tropical ecosystems, for instance, well-managed silvopastoral systems can exhibit soil carbon levels comparable to those of native forests (Lustosa Filho et al., 2024), aligning with the high structural complexity of the biodiverse silvopastoral system analyzed here.

In the global spectrum of carbon dynamics, biodiverse silvopastoral systems serve as high-performance models for carbon accumulation due to their species richness and functional diversity (Lustosa Filho et al., 2024). Unlike in simplified systems, the varied native tree species develop a multi-layered root system that extends through different depths, enhancing carbon storage in mineral-associated organic matter (MAOM), the soil's most stable and persistent fraction (Lustosa Filho et al., 2024). In silvopastoral systems, this process is further intensified by integrating leguminous species into both the arboreal and herbaceous components, increasing soil carbon and nitrogen stocks at deeper soil layers (Pessoa et al., 2025). This influx is crucial since MAOM formation relies on significant amounts of nitrogen for carbon stabilization via microbial pathways – a mechanism confirmed by the isotopic analysis across soil depths (Lustosa Filho et al., 2024). The resulting system is complex, promoting a steady transition toward self-sufficiency through land-use redesign, while prioritizing internal nutrient cycling and reducing external-input reliance (Dumont et al., 2013; Carvalho et al., 2024). This transition is mediated mainly by biodiversity and intensive *in situ* biomass management, which optimize ecosystem regulation services (Steinfeld et al., 2023).

Given the synergy between different legume growth forms, niche complementarity is essential for a self-sufficient system (Dumont et al., 2013). In biodiverse silvopastoral systems under intercropping, for example, the high-quality litter from leguminous species (lower carbon:nitrogen ratio) accelerates nutrient mineralization and enhances microbial carbon use efficiency (Marcondelli, 2019). This process is a key driver for carbon sequestration, as it promotes the formation of MAOM, while potentially offsetting emissions of greenhouse gases through an improved soil health and a reduced need for synthetic nitrogen (Lustosa Filho et al., 2024).

Although litter quantity may be similar across systems, the biodiverse silvopastoral system shows a significantly higher nutrient return (Marcondelli, 2019). This efficiency is partly explained by the system's microclimate (characterized by solar radiation buffering and soil moisture maintenance) and canopy architecture, which ensure that decomposition is driven by microbial pathways rather than by rapid oxidation (Pezzopane et al., 2015). This biological control maximizes carbon residence time in the soil (Marinho et al., 2020; Olaya-Montes et al., 2021).

Another key strategy in biodiverse silvopastoral systems is intercropping grasses with leguminous species, such as pigeon pea [*Cajanus cajan* (L.) Millsp.]. Compared with conventional pastures, this consortium has led to reductions of up to 70% in enteric methane emissions due to soil carbon sequestration (Furtado et al., 2023). By improving nutritional quality and reducing reliance on external inputs, such as protein supplements and synthetic fertilizers (Kaushal et al., 2025), this approach aligns with the low-input and self-sufficiency principles proposed by Dumont et al. (2013). The increased amount of nitrogen input from pigeon pea, for instance, helps stabilize the formation of soil organic matter (MAOM), limited by the element's presence. Thus, grass and legume intercropping acts as a dual-action tool (Furtado et al., 2023), lowering the carbon footprint per unit of animal product, while simultaneously building a robust and stable belowground carbon sink (Lustosa Filho et al., 2024). The integration of signal grass [*Urochloa decumbens* (Stapf) R.D.Webster] with specific tree legumes, such as gliricidia (*Gliricidia sepium* Kunth ex Steud.) and sabiá (*Mimosa caesalpiniifolia* Benth.), further enhances the system's synergy. According to

Lira Junior et al. (2020), these combinations optimize decomposition efficiency by stimulating microbial activity, effectively bridging the gap between biomass input and the stabilization of carbon in deeper soil layers. Therefore, the studied system functions as a self-regulating entity where biodiversity serves as both a carbon pump and a biological shield (Morales-Ruiz et al., 2025).

In forest stands composed of trees of varying ages, continuous recruitment – the constant replacement of older or dying trees by young ones – ensures a long-term carbon retention. However, in silvopastoral systems, this recruitment is a critical challenge due to livestock pressure (Cá et al., 2022). Specifically, in the biodiverse silvopastoral system, the high variability among native species, such as differences in growth rates and palatability, requires adaptive management rather than fixed schedules (Nicodemo et al., 2016). Therefore, to ensure the permanence of the carbon sink, it is essential to implement a strategic protection for natural regeneration or periodic replanting. Without a successful recruitment, the system's capacity for climate regulation becomes temporary.

For the biodiverse silvopastoral system to remain as a carbon sink, the model must move beyond transient carbon accumulation in surface layers, prioritizing biological and geochemical mechanisms that stabilize carbon in the subsoil and MAOM fractions (Lustosa Filho et al., 2024). This dual approach ensures forest successional continuity aboveground, while fostering deep-soil carbon stabilization belowground, defining the biodiverse silvopastoral system as a high performance strategy for long-lasting climate resilience (Steinfeld et al., 2023; Lustosa Filho et al., 2024). Ultimately, this synergy promotes the transition toward agroecosystems governed by the self-regulation of biological and geochemical fluxes, fulfilling the fundamental principles of ecological intensification and system self-sufficiency (Dumont et al., 2013; Kremen, 2020).

Multifunctionality and associated ecosystem services

The multifunctionality of the biodiverse silvopastoral system is not merely a collection of isolated benefits but an integrated result of biological and geochemical self-regulation (Dumont et al., 2013). Due to its functional diversity, the system optimizes resource use by utilizing natural processes to substitute chemical and mechanical inputs, establishing robust ecological regulatory mechanisms that enhance productivity, while providing essential ecosystem services (Chará et al., 2019; Nicodemo & Primavesi, 2019). This synergy fundamentally increases system resilience against climate change by buffering environmental extremes and maintaining stable nutrient cycles (Morales Ruiz et al., 2021; Kaushal et al., 2025).

The species-specific contribution to the system's dynamics is evident when integrating native functional groups. For instance, the inclusion of species such as baru tree (*Dipteryx alata* Vogel), *pequi* (*Caryocar brasiliense* Cambess.), and *cagaita* (*Eugenia dysenterica* DC.) has been shown to significantly enhance soil organic carbon and nutrient availability (Calil et al., 2016). Although leguminous trees primarily increase carbon stocks in the surface layer (0–10 cm), their impact on nitrogen stocks is much broader, occurring across the entire soil profile down to 1.0 m (Cá et al., 2022). This underground enrichment directly translates into system productivity and animal performance.

In the literature, Xavier et al. (2014) found that incorporating leguminous trees, such as mangium (*Acacia mangium* Willd.) and *jurema-branca* (*Mimosa artemisiana* Heringer & Paula), into silvopastoral systems significantly increased heifer live weight gain to 205 kg head per year, compared with 177 kg head per year in grass-only monocultures. Consistently, Furtado et al. (2023) observed a 57% increase in the average daily gain of Nellore cattle in pastures intercropped with pigeon pea. The benefits of this incorporation extend to dairy production as well: in silvopastoral systems with leucaena [*Leucaena leucocephala* (Lam.) de Wit], Sarabia-Salgado et al. (2020) reported a milk yield of 7.4 kg per day, a value nearly double that of 4.7 kg per day in monoculture pastures. This superior performance is sustained by an enhanced biological nitrogen fixation and an efficient nitrogen recycling.

In addition to nitrogen, the mobilization of calcium and phosphorus from *in situ* mulch into plant-available soil pools also drives the biodiverse silvopastoral system toward biological self-regulation (Steinfeld et al., 2023). The architecture of the system further optimizes the plant-animal-microclimate interaction. Grassland components allocate a significant carbon

amount to roots, deepening the soil carbon reservoir, while the partial cover provides moderate microclimate conditions, which are essential for animal welfare, ensuring optimal temperature and humidity levels that reduce heat stress and favor productivity (Pezzopane et al., 2019). Other authors have concluded that these internal synergies improve forage longevity and nutritional quality, effectively transforming the biodiverse silvopastoral system into a high-efficiency model that balances environmental health with an intensified animal production (Sarabia-Salgado et al., 2020; Cá et al., 2022; Furtado et al., 2023).

Aivalli et al. (2025) added that a healthy soil microbiome fosters a diverse food web that contributes to pest and disease control through mechanisms such as competition, predation, and parasitism. It is through these robust ecological regulatory mechanisms that functional biodiversity replaces external inputs in the analyzed biodiverse silvopastoral system. Within this environment, cattle exhibited a 38% decrease in horn fly (*Haematobia irritans*) infestations, resulting in an improved animal welfare and superior weight gain (Oliveira et al., 2017). The observed reduction is likely driven by an increased abundance of dung beetles (Coleoptera: Scarabaeidae) compared with open monoculture pastures (Giraldo et al., 2011). The multi-layered canopy of the system provides a buffered microclimate, characterized by lower soil temperatures and a higher humidity that favor beetle activity and survival. By rapidly burying and decomposing manure, these beetles disrupt the fly's reproductive cycle, while simultaneously accelerating nutrient mineralization (Duque-Vélez et al., 2022).

In addition to leading to biological regulation, the biodiverse silvopastoral system also functions as a strategic model to climate change adaptation by optimizing hydrological cycles and soil stability. This integration creates a structural buffer that mitigates the impacts of erratic weather patterns, reducing, for instance, surface runoff to less than 10% of precipitation, a much lower value than that of up to 48% losses through runoff in treeless pastures (Chará et al., 2019). By slowing horizontal water movement through an increased surface roughness and canopy interception, the biodiverse silvopastoral system facilitates groundwater recharge and creates a sponge effect (Chará et al., 2019; Nicodemo & Primavesi, 2019), which is vital for maintaining base flow during extended dry periods.

Another key feature of climatic resilience is the deep-water carbon pump. Native tree roots reaching depths of 2.0 to 8.0 m access water reserves unavailable to grasses, a clear example of niche complementarity (Pezzopane et al., 2015). This vertical stratification ensures that trees retain transpiration and air humidity even during severe droughts, reducing the overall evaporative demand on the forage component (Nicodemo & Primavesi, 2019). Consequently, the biodiverse silvopastoral system maintains system stability when conventional pastures would otherwise fail.

Soil stability is simultaneously optimized to withstand extreme rainfall events. The continuous accumulation of soil organic matter promotes stable aggregates that enhance aeration and infiltration, preventing erosive processes typical of degraded pastures (Aivalli et al., 2025). The management of functional-diversity promoting organisms, such as dung beetles and mycorrhizal fungi, also improves soil porosity and the long-term chemical stabilization of carbon in the MAOM fraction (Moreno-Gálvan et al., 2023).

Biodiverse silvopastoral systems play a critical role in biodiversity conservation by providing a habitat for species that tolerate moderate disturbance, preserving the germplasm of threatened species that can also be incorporated into production systems, while alleviating pressure on natural forests. Therefore, silvopastoral systems can enhance landscape connectivity and support the protection of native forest fragments (Nicodemo & Primavesi, 2019). By reducing firewood and saw timber within, for instance, such systems reduce the need to exploit natural forest remnants.

Another critical, yet overlooked ecosystem service of the biodiverse silvopastoral system, is the significant reduction of wildfire risk, a major threat to both biodiversity and carbon permanence in tropical landscapes. This mitigation occurs through two primary regenerative mechanisms: bioreduction of fine fuels, where livestock acts as biological mowers, grazing on dry grasses that typically serve as the primary fuel for fire spread (Oliveira & Abreu et al., 2021); and microclimatic buffering, in which the presence of tree rows reduces wind speed and maintains a higher relative humidity within the system (Pezzopane et al., 2015), creating a physical and climatic barrier that limits fire ignition and propagation. According to Batcheler et al.

(2024), the implementation of silvopastoral systems aimed at reducing fine fuels (i.e., pasture vegetation) that commonly propagate fires must strike a balance between tree density, forage production, and livestock carrying capacity. While specific experimental data on fire spread in native silvopastoral systems are still emerging, the structural design of the biodiverse silvopastoral system, balancing tree density and forage biomass, aligns with the integrated fire management strategies proposed by Batcheler et al. (2024). This proactive risk management is fundamental for ensuring that the carbon sequestered in the system remains stable over decades.

The multifunctional use of native trees also provides a socioeconomic safety net by providing non-timber forest products and high-value timber. Species such as *canafístula* [*Peltophorum dubium* (Spreng.) Taub.], *jequitibá-branco* [*Cariniana estrellensis* (Raddi) Kuntze, and *ipê-felpudo* [*Zeyheria tuberculosa* (Vell.) Bureau] represent long-term capital, and some of these species reach commercial maturity for timber within 15 to 40 years (Nicodemo et al., 2016). However, a significant gap remains in silvocultural recommendation tailored for integrated systems. Current knowledge often lacks precise data on optimal pruning and thinning schedules to maximize timber quality without compromising forage production. Addressing these technical gaps is vital to fully reach the regenerative potential of the biodiverse silvopastoral system, transforming it into a profile model that reconciles ecological and productive restoration with the economic needs of rural producers (Nicodemo & Primavesi, 2019; Bento et al., 2020; Carvalho et al., 2024).

According to presented findings, the management of an integrated landscape at property level is essential to address multiple objectives simultaneously, including food production, biodiversity conservation, climate change mitigation, and the delivery of ecosystem services. This approach emphasizes the management of landscapes in a way that promotes positive synergies among the aimed goals (Pinheiro & Nair, 2018; Nicodemo & Primavesi, 2019).

Concluding Remarks

The biodiverse silvopastoral system with native trees functions as a robust model for climate regulation and landscape restoration. The management of biological process, grounded in functional diversity, is the primary driver of the system's success. The integration of native leguminous trees and legume-intercropped pastures restores essential ecosystem services, evidencing that the transition from input-depend models toward process-based regulation is a viable and scalable pathway for resilient tropical agriculture.

This approach represents a crucial tool for aligning livestock production with environmental stewardship, contributing to the development of climate-smart landscapes at farm level by integrating both mitigation and adaptation strategies to address the impacts of climate change.

A critical knowledge gap remains regarding the evaluation of diverse ecosystem services through the functional management of biological processes. Future research should focus on monitoring system multifunctionality as a dynamic result of these processes, rather than treating services as isolated outputs. This approach is key to consolidating biodiverse silvopastoral systems as models for a regenerative and sustainable livestock production.

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Chief editor: Edemar Corazza
Edited by: Mírian Baptista

Data availability statement

Data in article: research data are available in the published article.

Declaration of use of AI technologies

During the preparation of this work, the authors used Gemini (Google, Mountain View, CA, USA) and Google NotebookLM for language refinement and structural organization of the manuscript. After this use, the authors reviewed and edited the content as needed and takes full responsibility for it.

Conflict of interest statement

The authors declare no conflicts of interest.

Acknowledgments

To Empresa Brasileira de Pesquisa Agropecuária (Embrapa), for support provided; to Instituto Brasileiro de Desenvoilvimento Sustentável (IABS) and to Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), for financial support (Grant 403947/2025-1).

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