

SILVOPASTORAL SYSTEMS WITH EUCALYPTUS FACING CLIMATE CHANGE

A NARRATIVE REVIEW OF BENEFITS, RISKS, AND APPLICABILITY IN THE PERUVIAN CONTEXT

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ABSTRACT: Climate change is one of the main threats to the sustainability of livestock systems in tropical and subtropical regions, where rising temperatures, irregular rainfall, and more frequent extreme weather events reduce grazing land productivity. Eucalyptus-based silvopastoral systems are promoted as a mitigation and adaptation alternative, although debate persists regarding their water balance and effects on biodiversity. This study critically analyzes scientific evidence published between 2020 and 2025 on the effects of eucalyptus-based silvopastoral systems on microclimate regulation, carbon sequestration, water balance, livestock productivity, biodiversity, and socioeconomic viability, with an emphasis on applicability to the Peruvian context. We conducted a narrative (non-systematic) literature review of studies published between 2020 and 2025, searching Scopus, Web of Science, SciELO, and Google Scholar in Spanish, English, and Portuguese, then thematically organizing 15 documents, including scientific articles, technical reports, and case studies. Available evidence suggests these systems can reduce air temperature and animal heat stress, increase carbon storage in biomass and soil, and improve productive indicators. However, these benefits are contingent on system design, site water availability, and the inclusion of native species. In conclusion, eucalyptus-based silvopastoral systems represent a promising alternative for Peruvian livestock farming under climate change, but their environmental and productive performance is conditional on technical management; further field evaluations with comparable metrics are recommended before generalizing adoption.

Keywords: silvopastoral, microclimate, *Eucalyptus urograndis*, climate mitigation.

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INTRODUCTION

Climate change has become a major stressor on agricultural systems worldwide, profoundly transforming their productive and ecological foundations. According to Bosi et al. (2020), rising temperatures, increasingly unpredictable precipitation patterns, more frequent prolonged droughts, and accelerated soil degradation are significantly altering rural production systems. Extensive livestock production, especially in tropical regions, is among the activities most sensitive to these disturbances because it depends heavily on natural pasture productivity. In this context, Andrade and Ibrahim (2003) highlight the importance of quantifying carbon sequestration in silvopastoral systems in response to global climate change, while Ghale et al. (2022) emphasize the broader role of agroforestry systems—of which silvopastoral systems are a variant—in landscape-scale carbon sequestration.

Given this highly vulnerable scenario, de Macêdo Carvalho et al. (2024) note that silvopastoral systems have emerged as a productive alternative geared toward sustainability, as they simultaneously integrate forestry, forage, and livestock components within a single management unit. Among the fast-growing forest species adopted in various Latin American countries, the genus *Eucalyptus* stands out because of its high productivity, economic value, and potential to mitigate climate change.

In Peru, Fuentes et al. (2022) note that the historical expansion of extensive livestock farming has been associated with severe soil degradation, particularly in the Amazon, the northern highlands, and various inter-Andean regions. In response, public and private entities have promoted silvopastoral systems with eucalyptus as a productive restoration strategy.

However, Chavan et al. (2024) caution that, despite growing interest in silvopastoral systems with eucalyptus, significant controversies persist in the scientific community about their long-term sustainability, particularly because of high water consumption and potential effects on local biodiversity when eucalyptus is established as a monoculture.

Despite the growing body of scientific research on silvopastoral systems with eucalyptus, the available literature is scattered across experimental studies, partial reviews, and regional economic assessments, with no synthesis that critically integrates—with an explicit focus on

Peru— the reported effects on the microclimate, carbon, water, productivity, biodiversity, and socioeconomic viability. This fragmentation is particularly problematic because, as detailed below, much of the available evidence pertains to silvopastoral or agroforestry systems in general—and not specifically to eucalyptus—and often fails to distinguish whether the reported effect corresponds to a climate change mitigation mechanism (e.g., carbon sequestration) or an adaptation mechanism (e.g., microclimate regulation, animal welfare). This fragmentation makes it difficult for decision-makers and producers to get a comprehensive overview of when these systems are effective and when they may have adverse effects.

Within this framework, this study constitutes a non-systematic narrative review of the literature published between 2020 and 2025, with the objective of critically analyzing the main scientific advances regarding silvopastoral systems with eucalyptus as a strategy for climate change mitigation and adaptation, incorporating results from experimental studies, reviews, and economic evaluations, with a special emphasis on their applicability in the Peruvian and Latin American contexts. As this is a narrative review, interpret its conclusions as a guiding synthesis of the current state of knowledge, not as an effect estimate supported by a formal assessment of evidence quality.

METHODOLOGY

Review design. We chose a narrative (non-systematic) literature review because the search and selection process was not conducted in accordance with a pre-registered protocol, nor did it follow the PRISMA 2020 guidelines. This methodological decision is explicitly stated to avoid a designation that the procedure actually carried out does not support.

Information Sources. The Scopus, Web of Science, SciELO, and Google Scholar databases were consulted, supplemented by institutional repositories specializing in the subject matter (INIA-Peru, CIFOR-ICRAF).

Search Strategy. Combinations of keywords in Spanish and English were used, linked by the Boolean operators AND/OR, including: (“sistema silvopastoril” OR “silvopastoral system*”) AND (‘eucalipto’ OR “Eucalyptus”) AND (“cambio climático” OR “climate change” OR “mitigation” OR ‘microclimate’ OR “carbon sequestration” OR “water balance”). We conducted the literature search throughout the development process, using combinations of keywords in Spanish and English with the Boolean operators AND and OR. The search strategy included terms related to silvopastoral systems, Eucalyptus, and climate change.

Time Period and Languages. We considered documents published between 2020 and 2025 in Spanish, English, and Portuguese (provided the abstract was available in one of the first two languages).

Eligibility Criteria. We included scientific articles, reviews, technical reports, and case studies that addressed silvopastoral systems with at least one eucalyptus component and reported on variables related to microclimate, carbon, water, productivity, biodiversity, or socioeconomic aspects. Documents without access to the full text or abstract were excluded, as were those focused exclusively on pure forest plantations without a livestock component.

Selection procedure. We selected documents by reviewing titles and abstracts, followed by a full reading of the preselected documents. We did not apply a PRISMA-style flowchart, as this was a narrative review; we acknowledge this as a methodological limitation (see

Discussion). Of the total documents identified, we ultimately included seven in the synthesis (see Table 1), which is fewer than the approximate estimate of twenty.

Extracted Variables and Categories of Analysis. We extracted the following information from each document: author and year, country or region, objective, methodological design, sample or unit of analysis, eucalyptus species, silvopastoral system configuration, variables studied, main results, and stated limitations. The information was organized into six thematic categories: (1) microclimate regulation, (2) carbon sequestration in biomass and soil, (3) water balance, (4) livestock productivity and animal welfare, (5) biodiversity and ecosystem services, and (6) socioeconomic viability.

Quality Assessment. No formal methodological quality assessment tool (e.g., GRADE or Cochrane checklists) was applied, which constitutes an explicit limitation of this study and an additional reason to classify it as a narrative review rather than a systematic review.

Synthesis of the information. The synthesis was conducted narratively and thematically, grouping findings by category of analysis and explicitly distinguishing results reported by the reviewed studies from interpretations formulated by the authors of this manuscript (Discussion section).

Scope and differentiation of the evidence. In organizing the findings, we explicitly distinguished evidence specific to eucalyptus systems from evidence relating to silvopastoral or agroforestry systems in general; where the source permitted, we also distinguished mitigation mechanisms (e.g., carbon sequestration) from adaptation mechanisms (e.g., microclimatic regulation, animal welfare) to climate change.

RESULTS

The reviewed studies are presented below, organized by analysis category. The Discussion section interprets these findings and provides an overall critical assessment. The studies summarized in Table 1 constitute a representative, though not exhaustive, sample of the documents reviewed, selected for their direct thematic relevance to eucalyptus systems, geographic and methodological diversity, and availability of quantifiable data; the full list of sources consulted appears in the References section.

Microclimate Regulation

Bosi et al. (2020) report that including trees in pastures regulates the environment by reducing direct solar radiation, moderating temperature fluctuations, reducing wind intensity, and limiting soil moisture loss through evaporation.

In silvopastoral systems with eucalyptus, de Macêdo Carvalho et al. (2024) measured reductions of up to 4 °C in air temperature during periods of peak solar radiation, along with increases in relative humidity; the authors of the original study associate these changes with a reduction in heat stress in cattle and improvements in feed intake.

Similarly, Morales-Ruiz et al. (2025) report that silvopastoral systems reduce soil CO₂ emissions, increase carbon stocks, and regulate the microenvironment in tropical grazing lands—results consistent with the microclimatic effects described above.

In the Peruvian Amazon, Fuentes et al. (2022) document that silvopastoral systems with eucalyptus help maintain vegetation cover during the dry season, reducing forage biomass losses.

Carbon Sequestration in Biomass and Soil

Orefice et al. (2025) report that incorporating trees into grazing lands increases carbon stocks in both aboveground biomass and the root system; according to that study, these systems can store between two and five times more carbon in total biomass than conventional grasslands (study conducted in the northeastern United States; the result should be interpreted as an international comparative reference and not as direct evidence for the Peruvian context).

Regarding soil carbon, a study conducted in the Peruvian Amazon (Salazar et al., 2024) that compared silvopastoral systems with conventional grazing systems reported slightly higher soil carbon stocks in the silvopastoral systems, with no statistically significant differences in all cases, suggesting a “potential” for improved carbon storage rather than a conclusive effect (see Table 1).

According to de Almeida Barbosa et al. (2025), multiple factors determine the rate of carbon accumulation: the eucalyptus species used, planting density, soil type, grazing management, and climatic conditions. These findings align with the broader literature on agroforestry systems, which recognizes their general mitigation potential through carbon sequestration (Ghale et al., 2022); however, as noted in the discussion, the net benefit depends on the plantation not replacing native forest.

Water Balance

Culqui et al. (2025) note that eucalyptus has high transpiration rates, which can lower the water table and compete with associated pastures for water in areas with low groundwater recharge.

In contrast, other studies indicate that in regions with high precipitation, the net effect on water resources may be limited or even positive, since tree shade reduces soil evaporation and promotes infiltration, thereby decreasing surface runoff. This variability shows that the hydrological effect of eucalyptus depends on the site, planting density, and system management.

Livestock Productivity and Animal Welfare

In the San Martín region (Peru), Junca Paredes et al. (2025) report increases of up to 25% in meat production per hectare in silvopastoral systems with eucalyptus under proper technical management, compared to degraded extensive systems

de Macêdo Carvalho et al. (2024) note that shade reduces the incidence of heatstroke and physiological stress, which translates into greater reproductive efficiency and increased daily weight gain and milk production. These results are consistent with those reported by

Prudêncio Lemes et al. (2021), who note that silvopastoral systems improve animal welfare and productive performance in beef production systems.

It should be noted that some eucalyptus species contain secondary compounds that may be toxic if ingested in large quantities; therefore, livestock access to direct grazing of leaves and bark must be regulated.

Biodiversity and Ecosystem Services

de Macêdo Carvalho et al. (2024) report a higher abundance of birds, pollinating insects, and soil microorganisms in silvopastoral systems than in open grasslands. However, Guamán Rivera et al. (2025) caution that when eucalyptus is established in large-scale monoculture systems, biodiversity may decline compared with systems that include native tree species.

Socioeconomic Viability

Junca Paredes et al. (2025) indicate that income diversification through the sale of timber, posts, firewood, or energy biomass reduces exclusive dependence on livestock farming. In the Peruvian context, experiences in San Martín, Amazonas, and Cajamarca suggest that these systems can double profitability per hectare compared to degraded systems, provided there is access to timber markets and technical support (reference figure obtained from specific case studies; it does not constitute a representative average at the regional or national level).

Table 1

Characterization of the studies included in the review (representative selection)

Author and year	Country/Region	Objective	Design	Eucalyptus species	SSP Configuration	Variables	Key finding	Limitations
Bosi et al. (2020).	Brazil	To evaluate the effect of SSPs on climate and production variables	Experimental field study	Eucalyptus (SSP)	Scattered trees in pastures	Microclimate, soil moisture	Lower air temperature and higher relative humidity under the canopy	Site-specific results; not generalizable to the entire country
Fuentes et al. (2022).	Peru (Amazon Region)	To analyze the progress and prospects of	Narrative review	Eucalyptus and native species	Various regional configurations	Vegetation cover, soil degradation	SSPs help maintain vegetation cover and	High heterogeneity among farms; lack of

Author and year	Country/Region	Objective	Design	Eucalyptus species	SSP Configuration	Variables	Key finding	Limitations
		SSPs in the Peruvian Amazon					reduce degradation during the dry season	comparable quantitative data
Culqui et al. (2025).	Not specified	To evaluate the hydrological impacts of eucalyptus in SSPs	Review/synthesis of hydrological studies	Eucalyptus spp.	Varies by study	Water table, transpiration	Possible decline in the water table in areas with low groundwater recharge	Site-dependent effect; not quantified for specific Peruvian conditions
Junca Paredes et al. (2025).	Peru (San Martín)	To evaluate the economic and productive performance of intensive SSPs	Case study/economic evaluation	Eucalyptus (intensive SSP)	Intensive system with technical management	Meat production, profitability	Reported increase of up to 25% in meat production per hectare	Result of a specific technical management practice; not representative of extensive systems
Orefice et al. (2025).	Not specified	To analyze carbon dynamics in SSPs	Comparative synthesis	Eucalyptus and other species	Various configurations	Carbon biomass and roots	SSPs store 2–5 times more carbon than conventional pastures	Wide range; contingent on not replacing native forest
de Macêdo Carvalho et al. (2024).	Not specified	To evaluate the ecosystem services provided by SSPs	Review	Various, including Eucalyptus	Mixed systems vs. monoculture	Biodiversity, nutrient cycle	Greater biodiversity in mixed systems; lower biodiversity in eucalyptus monocultures	Qualitative comparison; limited quantitative biodiversity data

Note. Created by the author.

Table 2

Silvopastoral Systems with Eucalyptus

Studies published in Peru over the past five years on silvopastoral systems with eucalyptus as a strategy to mitigate the effects of climate change on grazing lands, indicating their geographic scope, objective, and main contributions.

Year – Reference	Region – Species	Objective	Results / Contributions
2023. Potential use of Eucalyptus viminialis for carbon Labill.	Cajamarca, Peruvian Andes. Eucalyptus viminialis	To evaluate the carbon sequestration potential (above-ground biomass, soil) of a silvopastoral	E. viminialis showed good capacity for above-ground and soil carbon storage; it can function as a carbon

Year – Reference	Region – Species	Objective	Results / Contributions
sequestration in a silvopastoral system, Peru		system (SSP) with eucalyptus	reservoir, reconciling production and conservation.
2024. Soil carbon stock potential in pastoral and silvopastoral systems in the Peruvian Amazon (Salazar et al., 2024)	Peruvian Amazon, Cuñumbuqui District, San Martín	Compare soil carbon stocks between silvopastoral systems (SSP) and conventional pastoral systems (CPS)	SSPs tended to have higher soil carbon stocks than CPSs, although the differences were not statistically significant in all cases; the authors point to a “potential” for improvement in carbon storage.
2024. Silvopastoral systems in the Peruvian Amazon: a case study (CIFOR-ICRAF)	Jepelacio, Juan Guerra Soritor, Cuñumbuqui (San Martín), and Rodríguez de Mendoza (Amazonas)	Assess the role of silvopastoral systems in climate, biodiversity, and sustainable land use agendas	SSPs are underutilized and represent a key alternative for mitigating carbon emissions, promoting sustainable livestock production, and conserving biodiversity.
2022. Silvopastoral systems for livestock production in Peru	Various livestock-raising areas	Assess the agronomic performance of silvopastoral systems (production and environmental services)	The need for a balance between animal production and environmental services is emphasized, and the viability of SSPs as a sustainable model is supported.

Note. Created by the author.

DISCUSSION OF RESULTS

Overall, the reviewed evidence suggests that integrating trees, pastures, and livestock can help transform degraded grasslands into more stable agroecosystems, primarily through carbon sequestration, microclimate regulation, and improved animal welfare indicators. With regard to carbon sequestration, Andrade and Ibrahim (2003) argue that quantifying it in silvopastoral systems requires systematic monitoring based on permanent sampling plots whose shape and size depend on the density and spatial distribution of the trees, on biomass models that estimate above-ground carbon based on dasometric variables such as diameter at breast height and total height, and on the determination of soil organic carbon.

This approach is relevant for interpreting the reviewed evidence: estimates of carbon reserves and accumulation rates (Salazar et al., 2024; Orefice et al., 2025; de Almeida Barbosa et al., 2025) inherently depend on the choice of these components and their measurement procedures, so that differences between studies may reflect not only real contrasts between systems but also methodological differences. This reinforces the need for caution when interpreting the “potential” nature of the reported increases in edaphic carbon in the Peruvian Amazon (Salazar et al., 2024) and supports the recommendation that future studies in Peru adopt standardized and comparable monitoring protocols. It should be noted that Andrade and Ibrahim (2003) constitute a methodological reference and not an evaluation of eucalyptus-based systems; therefore, their contribution is limited to how carbon sequestration is measured and verified, and not to the magnitude of the effect.

With regard to carbon, Orefice et al. (2025) argue that accumulation rates in aboveground biomass and roots exceed those of conventional grazing systems, particularly in regions with high forest productivity; however, that same study warns that the net climate benefit may be reversed if the establishment of eucalyptus plantations involves the replacement of native forest, a scenario that must be explicitly avoided in any proposal for scaling up.

With regard to water, the apparent contradiction between studies reporting a decline in the water table (Culqui et al., 2025) and those reporting neutral or positive hydrological effects does not necessarily represent incompatible findings; rather, it reflects the strong dependence of these results on local soil and climate conditions, planting density, and the spatial design

of the system. Consequently, based on the available evidence, it is not possible to establish a general rule regarding the hydrological effect of eucalyptus that would apply to the entire territory of Peru.

Regarding biodiversity, the reviewed studies largely agree that eucalyptus monoculture systems limit the ecological benefits observed in mixed systems with native species (Macêdo Carvalho et al., 2024; Guamán Rivera et al., 2025). This supports the recommendation—not a definitive conclusion—to prioritize designs that combine eucalyptus with native forest species.

From a public policy perspective, evidence from pilot projects in Peru suggests that, without sustained technical and financial support, small-scale producers' adoption of these systems remains limited. Instruments such as payments for ecosystem services, green credits, and carbon certification could facilitate scaling up (Mayr et al., 2025), although the reviewed studies have not comparatively evaluated their effectiveness in the Peruvian context.

From a theoretical perspective, this review explicitly systematizes the evidence, distinguishing between mitigation mechanisms (carbon sequestration) and adaptation mechanisms (microclimatic regulation, animal welfare) in eucalyptus-based silvopastoral systems—a distinction that previous literature addresses less explicitly. From a practical standpoint, the synthesized findings offer guidance for designing promotion policies and for technical decision-making by producers and extension workers in the Peruvian context, particularly on prioritizing mixed systems with native species and basing adoption on local assessments of water availability.

Limitations of this review. As this is a narrative review, no predefined search protocol was applied, and no formal assessment of the methodological quality of the included studies was conducted; therefore, selection bias cannot be ruled out. Furthermore, the heterogeneity of study designs, eucalyptus species, and soil and climate conditions across the reviewed studies limits the ability to generalize the reported effect sizes (e.g., the 25% increase in meat production reported by Junca Paredes et al. (2025) corresponds to a specific context and should not be interpreted as a universally expected value).

CONCLUSIONS

The reviewed evidence suggests—though it does not constitute conclusive proof—that silvopastoral systems with eucalyptus may contribute to climate change mitigation on grazing lands, primarily due to their capacity for carbon sequestration in biomass and soil (Orefice et al., 2025).

From a production standpoint, the reviewed studies indicate that these systems can improve land-use efficiency, increase livestock productivity, and diversify income through forest production (Junca Paredes et al., 2025), although the reported figures are context-specific and should not be extrapolated without local verification.

The performance of these systems depends critically on proper technical design and site selection, particularly regarding water availability and soil conditions, since improper implementation can adversely affect water, soil, and biodiversity (Culqui et al., 2025).

Consequently, it is recommended to prioritize mixed systems that integrate native species and to avoid monoculture schemes (de Macêdo Carvalho et al., 2024).

Finally, given the narrative nature of this review and the absence of a formal assessment of the quality of the evidence, it is recommended that future research adopt comparable study designs and, if possible, systematic review protocols (PRISMA 2020) that allow for a more accurate quantification of the potential of these systems as a structural strategy for climate change mitigation in Peruvian and Latin American livestock farming. In particular, it is recommended that future studies: (a) report soil and climate conditions, planting density, and system management in a standardized manner so that results are comparable across studies; (b) incorporate study designs with explicit comparison groups and cost-benefit analyses using counterfactuals; and (c) establish medium-term water monitoring programs in eucalyptus silvopastoral systems across different regions of Peru, given the heterogeneity of water-related results identified in this review.

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