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Research paper

Integrating Biodiverse Silvopastoral Systems with Tax Law and Digital Technologies: Impacts on Welfare, Productivity, and Conservation in Tropical Livestock Systems

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Abstract

Biodiverse Silvopastoral Systems (BSSPs) offer a sustainable alternative for tropical livestock production by integrating trees, shrubs, and forage species with grazing animals. This study evaluated the impacts of BSSPs on productivity, animal welfare, and biodiversity in the Ecuadorian Amazon and examined how digital technologies and tax incentives can support their adoption. Data were collected from farms with varying levels of biodiversity integration and digital technology use. BSSPs increased milk yield to 10.1 L/cow/day, nearly 50% higher than conventional systems (6.8 L/day), and improved carcass weights by 14%. Despite lower stocking rates, net income per hectare was up to 28% higher, driven by improved animal performance and reduced veterinary costs. Animal welfare indicators also improved significantly. BSSP cattle exhibited lower body temperatures (38.3 °C vs. 39.1 °C) and respiration rates, associated with reduced thermal stress due to increased shrub cover (up to 42%) and canopy density, lowering the Temperature-Humidity Index (THI) below critical thresholds. Ecologically, BSSPs supported up to 21 tree species and doubled the Shannon Diversity Index (2.76 vs. 1.05) compared to monoculture systems. Digital tools—such as GPS collars, rumen sensors, and drones—were more commonly used in BSSPs, enhancing monitoring and management capacity. However, connectivity limitations and limited awareness of fiscal benefits still constrain broader adoption. This study highlights the potential of aligning agroecological practices with digital innovation and fiscal policy to transform tropical livestock systems. Promoting BSSPs through targeted tax incentives and precision technologies can simultaneously improve productivity, animal welfare, and ecosystem services.

Keywords: *Silvopastoral Systems; Tropical Livestock; Animal Welfare; Biodiversity Conservation; Tax Incentives; Precision Agriculture; Digital Technologies.*

1. Introduction

In the face of escalating climate change, accelerating biodiversity loss, and increasing pressure on tropical livestock production systems, there is an urgent need to redesign traditional agricultural models through an integrative, sustainable, and technologically driven approach (Rojas-Downing et al., 2017; Thornton & Gerber, 2010; Toulkeridis et al., 2020). Biodiverse Silvopastoral Systems (BSSPs) emerge as a promising strategy for tropical livestock production by integrating trees, shrubs, and herbaceous plants with grazing animals in a multifunctional landscape (Baldassini et al., 2018; Dablin et al., 2021; Mosquera-Losada & Rigueiro-Rodriguez, 2005). These systems promote ecological synergies that enhance pasture productivity, soil health, carbon sequestration, and animal welfare, offering a viable alternative to the conventional livestock systems characterized by monocultures, heavy reliance on agrochemicals, and practices that often degrade natural resources (Pinto et al., 2008; Montagnini et al., 2013).

BSSPs go beyond simple diversification; they represent a paradigm shift toward agroecological intensification, where natural processes such as nutrient cycling, microclimate regulation, and biological pest control are harnessed to increase the efficiency and sustainability of livestock production (Andersen et al., 2019; Onyeaka et al., 2024; Pezzopane et al., 2019). Research across Latin America and other tropical regions has shown that these systems can significantly increase milk and meat yields per hectare, reduce methane emissions per unit of product, and support habitat connectivity and wildlife conservation (Mauricio et al., 2019). In addition, BSSPs improve animal welfare by providing shade, thermal comfort, and natural foraging behavior, contributing to a holistic vision of ethical and productive livestock management (Sávio et al., 2011).

However, the adoption and scaling of BSSPs face several structural and institutional challenges (Mosquera-Losada & Rigueiro-Rodriguez, 2005). One of the key barriers lies in the limited integration of environmental and economic policy tools that recognize and reward the multifunctionality of these systems (Schwarz et al., 2022). In this context, tax law, particularly mechanisms related to environmental taxation, fiscal incentives, and land-use classifications, can play a pivotal role in fostering sustainable livestock transitions (I. Kovalchuk et al., 2021; Scherr et al., 2009). Properly designed tax frameworks can promote land stewardship by offering tax reductions or exemptions to producers who implement BSSPs, engage in ecosystem service provision, or reduce their environmental footprint (de Figueiredo et al., 2017; Martínez-salinas et al., 2024). Nevertheless, many national tax systems remain outdated, favoring intensive agriculture and lacking incentives for regenerative practices. Bridging this gap requires a robust dialogue between environmental science, agricultural economics, and legal frameworks (Bussoni et al., 2019).

Digital technologies, particularly those under the umbrella of Precision Livestock Farming (PLF), add another transformative layer to the development and monitoring of BSSPs (Akash et al., 2022; Neethirajan, 2024). Sensors, artificial intelligence, remote sensing, and data analytics offer unprecedented opportunities to quantify ecological benefits, track animal health and productivity, and generate real-time evidence for decision-making and policy implementation (Geng et al., 2024; Moriya et al., 2021). These tools can be harnessed to verify compliance with tax incentive schemes, document environmental performance, and facilitate access to climate finance and green certification programs (Hazwan et al., 2022). Furthermore, digital platforms can enhance transparency, farmer empowerment, and participatory governance in rural areas (Ezalia et al., 2020).

Integrating BSSPs with tax law and digital technologies forms an innovative framework. It simultaneously promotes productivity, conservation, and social equity in tropical livestock systems (Goncearuc et al., 2024). This approach is particularly relevant in tropical regions such as the Amazon, where livestock expansion has historically contributed to deforestation, greenhouse gas emissions, and rural inequality (de Figueiredo et al., 2017; González-Quintero et al., 2021; Guamán-Rivera et al., 2025). A strategic shift toward biodiverse, technology-enabled, and policy-supported systems could not only reverse these trends but also position tropical livestock as a key driver of sustainability and climate resilience. Recent contributions from tropical regions outside Latin America, such as Africa and Southeast Asia, have shown similar potential for integrating silvopastoral systems with fiscal incentives and digital tools (Neethirajan, 2024; Omurgazieva et al., 2024). Recent advances in precision agriculture have significantly enhanced the efficiency and sustainability of silvopastoral systems, integrating sensor technologies and data analytics to optimize resource use and animal welfare (Zhang et al., 2023). Concurrently, emerging green tax policies are incentivizing sustainable land use and biodiversity conservation, with innovative fiscal frameworks being implemented in various tropical regions worldwide (Kovalchuk & Kravchuk, 2019). Comparative studies from tropical Africa and Southeast Asia reveal similar challenges and opportunities in adopting silvopastoral practices, highlighting the importance of contextualized economic incentives and technology adoption strategies to maximize ecological and economic benefits (Khanna & Zilberman, 1997; Krawczyk et al., 2005). These interdisciplinary perspectives underscore the global relevance and adaptability of integrated approaches combining ecological sustainability, economic policy, and digital innovation. This article aims to analyse the combined impacts of BSSPs, progressive tax legislation, and digital technologies on animal welfare, livestock productivity, and biodiversity conservation in tropical ecosystems. By examining interdisciplinary case studies, reviewing legal instruments, and evaluating technological applications, we propose an integrative model for sustainable livestock development. Our analysis emphasises the need for coordinated action among farmers, policymakers, researchers, and technologists to unlock the full potential of BSSPs and address the complex challenges of tropical livestock systems in the 21st century.

2. Materials and methods

2.1. Ethical considerations

All participants were informed about the objectives of the study and provided their voluntary consent before participation. Confidentiality and anonymity were ensured throughout the process, and local knowledge was respected as part of an ethical commitment to the communities involved.

2.2. General approach

This study was designed using a mixed, interdisciplinary, and transdisciplinary approach, combining qualitative and quantitative methods to holistically assess the impacts of Biodiverse Silvopastoral Systems (BSSPs) on animal welfare, livestock productivity, and biodiversity conservation. The analysis also considered the integration of digital monitoring and management technologies, as well as relevant legal instruments in environmental and tax law (Park & Son, 2010; Payne & Jesiek, 2018). This combination of dimensions allowed for a comprehensive understanding of the subject from technical, ecological, regulatory, and technological perspectives.

2.3. Study area and units

The fieldwork was conducted in the tropical region of Ecuador, focusing on the province of Orellana, which is characterized by significant livestock activity, high biodiversity (Peralta et al., 2024), and the presence of various silvopastoral initiatives at different stages of development (Vargas-tierras et al., 2018). A total of three to five representative livestock farms were selected based on the following criteria: a) integration of trees, shrubs, and grasses, b) Implementation or potential use of digital technologies, and c) Participation in environmental programs or interest in green tax incentives.

3. Data collection

a) Document and Policy Review_ extensive review was conducted of national and local laws, regulations, and public policies related to: Green tax incentives and payments for ecosystem services; Agricultural and livestock land-use classification; Sustainable livestock development and rural digitization programs; Sources from Ecuador, Colombia, and Brazil were included for comparative analysis.

b) Semi-Structured Interviews_ Interviews were carried out with farmers, technical advisors, local authorities, and representatives from public institutions. Key topics included: Perceived benefits and limitations of BSSPs; Barriers to the adoption of digital technologies; and Awareness of and access to fiscal or environmental incentives.
c) Evaluation of Productive, Ecological, and Animal Welfare Indicators_ Data collection at each farm included: Productivity: Milk or meat production per animal and hectare. Animal welfare: Body temperature, respiration rate, behavior related to thermal comfort (shade access, resting time, feeding behavior). Vegetation biodiversity: Species richness and diversity of trees and shrubs, vegetation cover, and Soil quality: Organic matter content and visible erosion indicators (when applicable).
d) Assessment of Digital Technology Use, The use or potential adoption of various technologies was documented, such as: Ruminal sensors, GPS collars, thermal cameras, drones; Mobile apps for health and production management; Digital platforms for traceability and environmental monitoring and aspects such as cost, connectivity, accessibility, and farmer engagement with technology were also assessed.

4. Data analysis

Quantitative data were analysed using descriptive statistics (means and standard deviations) and comparative methods such as t-tests and correlation analysis to examine the relationships among productivity, biodiversity, and technology use. Simultaneously, qualitative data obtained from interviews and policy document reviews were coded and thematically analysed using NVivo software, enabling the identification of key patterns and categories across diverse participants and contexts. Additionally, geospatial analysis conducted with QGIS allowed for the mapping of Biodiverse Silvopastoral Systems (BSSPs), assessing their spatial distribution, overlap with conservation areas, and potential contribution to ecological connectivity within the studied landscapes.

5. Results

The data in Table 1 demonstrate that BSSPs outperform conventional systems in both milk and meat productivity on a per-animal basis, despite having slightly lower stocking rates. BSSP 2 shows a milk yield of over 10 liters per cow per day—nearly 50% higher than the conventional system, indicating that better forage quality, shade availability, and animal comfort may play a significant role in improving metabolic efficiency. Similarly, carcass weights are noticeably higher in BSSPs, which could be attributed to reduced heat stress and access to a more diverse and nutritionally rich diet. Interestingly, although BSSPs operate at a lower animal density (AU/ha^{-1}), their net income per hectare is higher, suggesting that the integrated system improves economic returns through enhanced animal performance, lower veterinary costs, and possibly better product quality (e.g., organic, grass-fed premiums). These findings challenge the notion that productivity must be achieved through intensification by numbers and instead support ecological intensification as a viable path.

Table 1: Milk and Meat Productivity in Biodiverse Silvopastoral Systems (BSSPs) and Conventional Systems

System	Milk Yield (L/cow/day)	Carcass Weight (kg/animal)	Stocking Rate (AU/ha)	Net Income (USD/ha/year)
BSSP 1	9.2 ± 1.1	205.3 ± 15.4	1.6	925.0
BSSP 2	10.1 ± 1.4	214.8 ± 12.9	1.8	1,012.5
Conventional	6.8 ± 0.9	188.5 ± 10.7	2.2	790.0

BSSP1: Moderately diversified system with 18 tree species and 35% shrub cover; BSSP2: Highly diversified system with 21 tree species and 42% shrub cover; Conventional = monoculture.

Table 2 provides strong evidence that BSSPs contribute significantly to reducing heat stress in tropical cattle. The THI values remain in a moderate stress range in BSSPs, while the conventional system reaches values consistent with high thermal stress. This correlates with elevated body temperatures and increased respiration rates in conventional cattle, which are physiological signs of heat strain. Behavioral observations further reinforce this difference: animals in BSSPs showed calm and productive behavior, either lying down in comfort or actively grazing, while those in the conventional system were agitated and sought shelter, indicating discomfort and suboptimal conditions. This chronic stress can negatively impact feed intake, immunity, fertility, and milk production. The results validate the ecological function of trees and shrubs as natural cooling infrastructure, emphasizing their role in animal welfare.

Table 2: Animal Welfare Indicators During Peak Heat Stress Periods

System	THI (Temp.-Humidity Index)	Body Temperature (°C)	Respiration Rate (breaths/min)	Observed Behavior
BSSP 1	72.5 ± 3.1	38.5 ± 0.3	52 ± 5	Calm, lying under a tree's shade
BSSP 2	71.2 ± 2.8	38.3 ± 0.2	49 ± 4	Grazing actively in shaded areas
Conventional	78.6 ± 4.5	39.1 ± 0.5	65 ± 6	Restless, seeking artificial shade

BSSP1: Moderately diversified system with 18 tree species and 35% shrub cover; BSSP2: Highly diversified system with 21 tree species and 42% shrub cover; Conventional = monoculture.

The data from Table 3 confirm the ecological richness embedded in BSSPs compared to conventional systems. Both tree species richness and canopy coverage are significantly higher in the BSSPs, particularly in BSSP 2, which registers over 60% canopy cover and 21 tree species. These structural elements contribute to habitat heterogeneity, shade provision, nutrient cycling, and resilience to climate variability. The Shannon Diversity Index (H') further reflects a more balanced and complex ecological network in BSSPs. In contrast, the conventional system—with only 5 tree species and minimal canopy—resembles a monoculture in terms of biodiversity, increasing its vulnerability to pests, soil degradation, and climatic extremes. The findings support the hypothesis that silvopastoralism not only provides productive benefits but also aligns livestock systems with biodiversity conservation goals.

Table 3: Vegetation Structure and Biodiversity Indicators in BSSPs

System	Tree Species Richness	Shrub Cover (%)	Canopy Coverage (%)	Shannon Diversity Index (H')
BSSP 1	18	35	52	2.38
BSSP 2	21	42	61	2.76
Conv	5	8	15	1.05

BSSP1: Moderately diversified system with 18 tree species and 35% shrub cover; BSSP2: Highly diversified system with 21 tree species and 42% shrub cover; Conventional = monoculture.

Table 4 highlights the varying degrees of digital technology adoption among the systems. BSSP 2 stands out for its integration of both remote-sensing tools (drones) and livestock-specific sensors, suggesting a higher level of investment in Precision Livestock Farming (PLF). Despite connectivity limitations (3G access), this system demonstrates how producers can creatively implement digital tools even in rural settings. In contrast, the conventional farm lacks any form of digital monitoring, which may hinder decision-making, traceability, and early detection of health or environmental risks. BSSP 1 uses GPS collars and mobile apps, showing moderate engagement with digital agriculture. These results underline a positive relationship between ecological complexity and technological innovation—producers investing in BSSPs appear more inclined to adopt precision tools, possibly due to better advisory support or alignment with sustainability programs. However, infrastructure barriers such as poor internet access remain critical challenges for broader PLF adoption in the tropics.

Table 4: Adoption of Digital Technologies Across Study Systems

System	GPS Collars	Rumen Sensors	Mobile Apps	Internet Access	Use of Drones
BSSP 1	Yes	No	Yes	Stable (4G)	No
BSSP 2	Yes	Yes	Yes	Limited (3G)	Yes
Conventional	No	No	No	Unstable (2G)	No

BSSP1: Moderately diversified system with 18 tree species and 35% shrub cover; BSSP2: Highly diversified system with 21 tree species and 42% shrub cover; Conventional = monoculture.

6. Discussion

Integrating Biodiverse Silvopastoral Systems with Tax Law and Digital Technologies refers to a holistic approach that combines the agricultural practice of silvopastoralism, which integrates trees, shrubs, and livestock to enhance productivity, welfare, and conservation in tropical livestock systems (Améndola et al., 2019; Silva-olaya et al., 2022; Guamán-Rivera et al., 2024). Silvopastoral systems, which blend tree cultivation with livestock production, have emerged as a promising agricultural practice that not only enhances productivity but also offers significant ecological benefits (Baldassini et al., 2018; Fuentes et al., 2023). These systems combine herbage, shrubs, and tree layers with grazing animals, resulting in multifunctional landscapes that can improve overall land productivity by up to 55% despite a reduction in individual forage yield (Montagnini et al., 2013; Murgueitio et al., 2014). The integration of trees in pasture systems is known to enhance water quality, soil quality, and carbon sequestration while modifying the microclimatic conditions to create a more resilient environment for livestock (Flores-coello et al., 2023; Guamán-Rivera et al., 2024b).

The adoption of silvopastoral systems can provide various ecosystem services, such as improved biodiversity and enhanced carbon sequestration, which are crucial in combating climate change (Martínez et al., 2014). Moreover, these systems can contribute to higher farm gate returns and reduced production costs through the diversification of income sources, which is increasingly important in the current challenging agricultural economy (Giro et al., 2019). By offering a richer and more sustainable environment for livestock, silvopastoral systems can also improve animal welfare, as they create conditions that are less stressful for animals, particularly under the impacts of elevated environmental temperatures (Guamán-Rivera et al., 2024a). Despite the clear advantages of silvopastoral systems, several barriers hinder their widespread adoption. Farmers often express uncertainties regarding the integration of these systems due to knowledge limitations about their benefits and practical implementation (Mosquera-Losada & Rigueiro-Rodriguez, 2005). Focus group discussions reveal that while there is a growing interest in diversifying agricultural practices, farmers remain cautious about the transition due to economic risks and regional resource constraints (Lima et al., 2019). Understanding these dynamics is crucial for designing effective educational outreach and policy interventions that can support the adoption of silvopastoral practices (Rosales, 2014).

The role of government incentives and subsidies is paramount in encouraging the adoption of biodiversity-friendly agricultural practices like silvopastoral systems (Hyland et al., 2014). Economic instruments such as targeted subsidies can reduce the perceived risks associated with transitioning to these integrated systems, ultimately promoting environmental sustainability and improving rural livelihoods (Geng et al., 2024). Additionally, leveraging digital technologies for monitoring and managing silvopastoral systems can provide farmers with valuable insights into pasture growth and livestock health, thereby enhancing their decision-making capabilities and increasing the overall efficiency of these systems (Zhang et al., 2020; Moriya et al., 2021).

Tax law plays a critical role in shaping agricultural practices, particularly in the context of integrating biodiverse silvopastoral systems within tropical livestock systems (Omurgazieva et al., 2024; Robles-Rodríguez et al., 2019). The implementation of these systems can be significantly influenced by various tax incentives designed to encourage environmentally sustainable practices and improve farm productivity (I. Kovalchuk et al., 2021; Rajakovi et al., 2025). Federal income tax laws offer a range of incentives, such as increased deductions from taxable income and lower tax rates on certain types of income, to promote the adoption of conservation and climate-smart practices in agriculture (Scherr et al., 2009). These incentives are particularly beneficial for farmers and landowners looking to implement biodiverse silvopastoral systems, which enhance both biodiversity and productivity. Tax rules related to the implementation of conservation practices depend on the nature of the activity and the method of funding. For instance, farmers may deduct ordinary and necessary expenses associated with their trade or business. Additionally, the Internal Revenue Code (I.R.C.) $ 175 allows for the deduction of certain expenses related to conservation practices, which can include improvements made to the land for environmental purposes. Other forms of support, such as cost-share payments under various conservation programs, may also be excludable from income, further incentivizing landowners to adopt sustainable practices (Ansong et al., 2024). The concept of green taxes—taxes imposed on environmentally harmful activities can also support the integration of biodiverse silvopastoral systems. Revenue generated from these taxes can be reinvested in conservation initiatives or used to provide financial incentives for sustainable agricultural practices. Such policies not only help mitigate the ecological impact of livestock farming but also promote practices that sequester carbon and enhance ecosystem services (Huertas et al., 2021). In Ecuador, the Environmental Incentives Law and Article 505 of the Organic Code of Territorial Organization and Autonomy (COOTAD) allow municipalities to apply property tax reductions for landowners who conserve forest cover or provide ecosystem services. However, the implementation of these incentives remains uneven and poorly communicated at the local level (Lechón Sánchez, 2023).

Digital technologies are transforming agricultural practices by enhancing efficiency, productivity, and sustainability in farming operations. These technologies reduce labor-intensive tasks and improve working conditions, making agriculture more attractive to current and prospective farmers (Abiri et al., 2023). By implementing digital tools, farmers can optimize the management of resources such as water, energy, and fertilizers, leading to improved yields and reduced input costs (Mayerfeld et al., 2023; Schahczenski, 2022). A significant advantage of digital technologies is their capacity for data collection, storage, and analysis. These systems allow for the retention of vast amounts of data, including numerical, textual, and multimedia information, which can be shared and interpreted across various platforms (Piñeiro et al., 2020). The integration of machine learning, artificial intelligence (AI), and the Internet of Things (IoT) enables farmers to analyze complex datasets, leading to better decision-making processes and more effective management practices (Castle et al., 2022).

However, successful implementation relies heavily on standardized data categorization and management practices to ensure that collected data can be easily accessed and utilized. One limitation of this study is the small sample size (three to five farms), which may constrain the generalizability of the findings. Future research should incorporate multi-site studies across diverse ecological zones and management systems to validate and scale the observed benefits of BSSPs.

7. Conclusions

Biodiverse Silvopastoral Systems (BSSPs) enhance productivity, animal welfare, and biodiversity in tropical livestock systems. Their integration with digital technologies improves management and traceability, while targeted tax incentives can foster broader adoption. This interdisciplinary approach demonstrates that aligning agroecology, informatics, and fiscal policy is essential to achieving sustainable and resilient livestock production in the tropics.

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Conflict of interest

The authors declare no conflict of interest.

Ethical statement

This article does not contain any studies that require ethics committee approval.
Availability of data: The data is available from the corresponding author, who can make it available on request.

Consent to participate

All participants consented to this research study

Consent for publication

All authors submitted consent to publish this research article

SDGs addressed

Zero Hunger; Health and Welfare; Responsible Production and Consumption.

Policy referred

Feed and Food Safety Regulations; One Health and Animal Welfare Policies.

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