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Article

Economic Evaluation of an Intensive Silvo-Pastoral System in San Martín, Peru

Running title: Economic Evaluation of a Silvo-Pastoral System in Peru

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Abstract: The cattle sector plays a critical role in Peru's agricultural economy, yet it faces challenges related to low productivity and environmental degradation. Sustainable alternatives like silvo-pastoral systems (SPS) offer promising solutions to enhance both economic returns and ecological outcomes in cattle farming. This study examines the economic and environmental viability of intensive SPS (SPSi) compared to traditional monoculture grass systems in San Martín, Peru. SPSi, which integrate grasses, legumes, shrubs, and trees, have the potential to enhance cattle farming profitability while simultaneously offering environmental benefits such as improved soil health and reduced greenhouse gas emissions. Through a discounted cash flow model over an eight-year period, key profitability indicators—Net Present Value (NPV), Internal Rate of Return (IRR), Benefit-Cost Ratio (BC), and payback period—were estimated for four dual-purpose cattle production scenarios: a traditional system and three SPSi scenarios (pessimistic, moderate, and optimistic). Monte Carlo simulations were conducted to assess risk, ensuring robust results. Results show that the NPV for the traditional system was a modest US\$61, while SPSi scenarios ranged from US\$9,564 to US\$20,465. The IRR improved from 8.17% in the traditional system to between 26.63% and 30.33% in SPSi scenarios, with a shorter payback period of 4.5 to 5.8 years, compared to 7.98 years in the traditional system. Additionally, SPSi demonstrated a 30% increase in milk production and a 50% to 250% rise in stocking rates per hectare. The study recommends promoting SPSi adoption through improved access to credit, technical assistance, and policy frameworks that compensate farmers for ecosystem services. Policymakers should also implement monitoring mechanisms to mitigate unintended consequences, such as deforestation, ensuring that SPSi expansion aligns with sustainable land management practices. Overall, SPSi present a viable solution for achieving economic resilience and environmental sustainability in Peru's cattle sector.

Keywords: intensive silvo-pastoral systems; economic evaluation; sustainable cattle farming; improved forages; profitability indicators; Montecarlo simulation; environmental sustainability; dual-purpose cattle

1. Introduction

The agricultural sector contributes 6.4% to Peru's Gross Domestic Product (GDP) (BCRP, 2021), with livestock accounting for 36.5% of this share. Within the livestock sector, the poultry industry (including poultry, chickens, and eggs) dominates at 42.5%, while cattle and raw milk represent 4% and 4.5%, respectively (MIDAGRI, 2023a). Nearly half of the country's dairy production operates within a context of business and technical informality, which negatively impacts both product quality and profitability in the livestock industry (Zavala Pope, 2010). Peru also has the lowest per capita

beef consumption in South America at 5.9 kg per person per year, a figure that is well below the national consumption rates for chicken (51.5 kg per person per year) and fish (18.7 kg per person per year), and closely aligned with pork consumption at 5.8 kg per person per year (MIDAGRI, 2019, 2023a).

San Martín province, located in northeastern Peru, has a relatively small cattle sector compared to its dominant poultry industry. Livestock contributes 14.8% to the province's agricultural GDP, with beef and milk accounting for 2.4% and 1.3%, respectively, while poultry represents a significant 8.5% share (BCRP, 2023b). In San Martín, cattle farming predominantly relies on dual-purpose systems. However, the widespread use of extensive farming practices results in poor animal nutrition, which in turn leads to low productivity and quality levels (DRASAM, 2007). Environmentally, the region has been heavily impacted by deforestation (Echevarría et al., 2019). Despite these challenges, the growing market potential presents a significant opportunity for economic development within the cattle sector but also a threat to sustainability. Implementing more productive and efficient systems could revitalize cattle farming in the region but if not well-managed lead to more deforestation and environmental degradation.

One promising alternative for sustainable growth is the adoption of silvo-pastoral systems (SPS). These systems not only enhance productivity and income but also offer environmental benefits, such as reduced per area greenhouse gas emissions, increased biodiversity, and microclimatic regulation, among others (Cuevas-Reyes et al., 2020; Gomes da Silva et al., 2021; Jose & Dollinger, 2019; Lemes et al., 2021; Peri et al., 2016). As a result, SPS have emerged as a cornerstone of agrarian policy aimed at fostering sustainable cattle farming systems (MIDAGRI, 2023b). Among the different types of SPS, intensive SPS (SPSi) combine grasses, legumes, shrubs, and trees for animal nutrition, allowing for intensified production while mitigating the environmental impact of cattle farming (Chará et al., 2018). The additional components to grasses offer a series of advantages. Perennial legumes fix their nitrogen, contributing to greater meat or milk production (Lagrange et al., 2021). Likewise, they reduce the environmental impact since they depend less on synthetic fertilizers (Thilakarathna et al., 2016). With the inclusion of trees, SPSi can provide microclimatic regulation, reduce wind speed, solar radiation, and thermal stress during periods of high temperature (Schinato et al., 2023).

For the region, several analyses and evaluations have highlighted the technical advantages of SPSi (Echevarría et al., 2019; Erazo, 2023; Roque Alcarraz et al., 2022). However, a deeper investigation into the economic performance of these systems is needed, as this is a critical factor for producers when considering the adoption of new technologies. Implementing a SPSi requires new investments, making it essential to determine whether the resulting income compensates for and exceeds these additional expenses. In Peru, particularly in San Martín province, such economic analyses remain scarce. Given this context, the objective of this study is to carry out an economic evaluation of a SPSi in the Tarapoto municipality, located in San Martín province. The system under analysis is a dual-purpose cattle system with Girolando cattle and was established on an area of 2.5 hectares. Its components include the grass *Urochloa brizantha* cv. Marandú, which covers 7,200 m² (72%) per hectare, the legume *Centrosema macrocarpum* covering 800 m² (8%) per hectare, the shrub *Tithonia diversifolia* covering 1,500 m² (15%) per hectare, and a range of timber trees occupying 500 m² (5%) per hectare. The trial was designed to reflect regional production conditions. The selection of system components and the projections of data on productivity, costs, and expected income are based on expert opinions, scientific literature, commercial market information, and official statistical data (Durango et al., 2021; Mahecha et al., 2007; MIDAGRI, 2023a; Rivera et al., 2015, 2022, 2023; Rogerio et al., 2017).

The economic evaluation includes four scenarios. The first is the baseline technology, which is the traditional system, a monoculture of the grass *Urochloa brizantha* cv. Marandú. The other three are the described SPSi under pessimistic, moderate, and optimistic scenarios. The definition of the scenarios corresponds to expectations of improvements in milk and beef productivity. Through a discounted cash flow model over 8 years, profitability indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), Benefit-Cost Ratio (BC), and payback period (PR) were estimated for

each of the scenarios. Monte Carlo simulations were conducted to incorporate probability elements into the analysis, providing greater robustness to the results.

Apart from this introduction, the document is structured as follows: Section 2 provides an overview of cattle farming in the Peruvian Amazon region, with a particular focus on San Martín, and explores the motivations behind promoting the adoption of SPS in the region. Section 3 outlines the materials and methods used for the economic evaluation and describes the scenarios studied. Section 4 presents the results, which are then compared with findings from the literature in the discussion in Section 5. Finally, the study's conclusions and recommendations are presented in Section 6.

2. Cattle Farming in San Martín Province

According to MIDAGRI (2023a), the national cattle population in 2022 was estimated at 5,862,308 animals, with 945,553 milking cows. San Martín province accounts for 213,453 cattle, representing 3.64% of the national total. In terms of milking cows, the region has 20,406, which corresponds to 2.16% of the national total. In Peru's milk market, the demand for raw milk is driven by industrial companies such as Leche Gloria, Laive, and Nestlé Peru, followed by several medium and small-scale companies. These industries collectively process 48% of the national production. Another 42% is handled by approximately 6,500 artisanal plants throughout the country, of which only about one-tenth are considered formal. The remaining 10% of production is used for calf feeding and family consumption (INDECOPI, 2022).

2.1. Motivation to Encourage the Adoption of SSP in San Martín Province

In the provinces of Amazonas and San Martín, production units are typically small, generally covering less than 10 hectares (Alegre et al., 2019; Pizarro et al., 2020). Regarding pasture performance, over 70% of the secondary forests in the Peruvian Amazon ecoregion consist of low-productivity native pastures, degraded improved pastures, and areas at various stages of recovery. The absence of technical management, animal overstocking, and overgrazing have led to nutrient depletion, negatively impacting soil quality. Deforestation for the creation of pastureland is a recurring issue. Currently, extensive grazing remains the dominant practice in these regions. SPS offer a sustainable solution by promoting more efficient land management (Alegre et al., 2017; Echevarría et al., 2019).

Some experiences in San Martín, evaluating *Urochloa brizantha* and leguminous shrub species in living fences, shading, and protein banks, have demonstrated acceptable performance results (Roque Alcarraz et al., 2022). Additionally, other studies in the region have analyzed silvo-pastoral systems (SPS) incorporating *Urochloa decumbens*, *Inga edulis* (Guaba trees), and *Eucalyptus* species, in both dispersed arrangements and as living fences. The dispersed trees were remnants of those previously used for timber, firewood, and construction materials. Living fences have been established with a focus on cattle farming, serving to delimit pastures and provide shade for animals. Despite these positive examples, such SPS arrangements remain underutilized, and there is limited technical training available for producers in the region. As a result, these systems are often implemented spontaneously, without institutional support or follow-up, and their benefits have yet to be fully quantified (Echevarría et al., 2019).

Although SPS are not widely known, local producers in San Martín implement some of their techniques, such as living fences to manage cattle and as a source of feed and protection (Alegre et al., 2019). In the context of extensive cattle farming and limited diversity in feeding systems, there are significant opportunities to further develop these technologies. One positive externality is the environmental impact of these transformations. The work of Marcelo-Bazán et al. (2022) highlights the role of trees in mitigating greenhouse gases. For example, *Eucalyptus viminalis* has shown potential for carbon capture in an SPS in northern Peru. Providing empirical evidence on the economic and environmental viability of SPS is crucial to promoting wider adoption.

2.2. Intensive Silvo-Pastoral Systems

SPS combine tree cultivation with cattle farming, providing shade for animals, complementing their diet, and improving their overall living conditions (Grebner et al., 2021). The primary goal of SPS is to enhance efficiency while minimizing the environmental footprint of cattle farming (Campanhola & Pandey, 2019). Among the various SPS configurations, notable arrangements include living fences, dispersed trees and shrubs within pastures, protein banks, intensive silvo-pastoral systems (SPSi), and windbreaks (Libreros, 2015).

The particular focus of this study is on the economic evaluation of SPSi. According to COFUPRO (2014) and IICA et al. (2016), SPSi enhance the production of high-quality forage, reduce production costs, increase productivity per hectare, and promote biodiversity. Libreros (2015) defines SPSi as an agroecological system composed of three layers, strata, or levels. The upper layer consists of native, fruit, or timber trees, which contribute by reducing cattle heat stress through shading, providing protection against strong winds, and lessening the impact of raindrops, thus mitigating soil erosion. These trees also serve as refuges for wildlife, facilitating biological pest control, and offer additional income opportunities, such as through the sale of timber or fruit. The second layer comprises leguminous shrubs, known for their high protein content. These shrubs often have flexible stems to prevent breakage during grazing. In the lowest layer, grasses are used for grazing, often mixed with legumes, which enrich the diet and contribute nitrogen and organic matter to the soil. The environmental impact of adopting an SPSi is substantial. The additional plant matter and the increased root density in the system improve water retention, carbon content, and overall soil quality (Campanhola & Pandey, 2019).

3. Materials and Methods

This section outlines the methods applied for the economic analysis conducted for both the traditional system and the SPSi. First, the characteristics of each technology and the assumptions used for their evaluation are presented. Following this, the discounted cash flow model and the probabilistic techniques applied to assess different productivity scenarios are explained.

3.1. Description of Evaluated Technologies

The system analyzed is based on a 2.5-hectare trial in San Martín province. The trial was designed to be representative of the region, reflecting its specific environmental and productive conditions. It is important to note that this region faces agroclimatic risks, such as increasingly prolonged droughts, which particularly affect the dominant sandy soils (Barrios-Pérez et al., 2023). These soil conditions typically require additional irrigation and inorganic fertilizers, which increase the environmental impact of cattle farming (Huang & Hartemink, 2020; Osman, 2018). Therefore, the SPSi, as proposed in this study, is a plausible alternative to mitigate these challenges.

Two production systems are evaluated in this study. The first is a traditional system, representative of San Martín province, consisting of a monoculture of *Urochloa brizantha* cv. Marandú as forage grass. The second system is an SPSi, which includes *Urochloa brizantha* cv. Marandú as the primary pasture, the legume *Centrosema macrocarpum*, the shrub *Tithonia diversifolia*, commonly known as Botón de Oro (Mexican sunflower), and a set of timber trees. The main characteristics of these system components are described below.

The grass *Urochloa brizantha* cv. Marandú serves as the baseline technology for this evaluation. Originating from a volcanic region in Africa, where soils have favorable fertility levels, this cultivar was introduced and released in Brazil (EMBRAPA, 1984). It has since been widely adopted across the American tropics. Key characteristics of *Urochloa brizantha* cv. Marandú include its resistance to spittlebug, a requirement for soils with intermediate to high fertility, and its poor tolerance to waterlogging (Cook et al., 2020). In Peru, experiences have shown that this cultivar associates well with legumes and is highly palatable to cattle due to its leaf content, making it well-accepted by livestock. Currently, it is the second most widely planted forage and ranks first in sales within the

country (MIDAGRI, 2023c). According to Perulactea (2015), *Urochloa brizantha* cv. Marandú has demonstrated strong performance in the soils of Alto Mayo, located in San Martín. Its superior qualities compared to other materials, such as *Urochloa decumbens*, have made it the most widely used forage in this region. In the evaluated SPSi, an area of 7,200 m² (72%) per hectare was established with *Urochloa brizantha* cv. Marandú.

The legume used in the SPSi is *Centrosema macrocarpum*, which is well-suited to highly acidic and low-fertility soils. It demonstrates drought tolerance, high nutritional value, and resistance to major diseases affecting *Centrosema* species (Cook et al., 2020). Legumes are valuable for providing cattle with essential micronutrients, plant-based proteins, and minerals (Raza et al., 2020). One of their most significant contributions is their ability to fix atmospheric nitrogen into the soil, enhancing the agroecosystem's nitrogen levels. This natural nitrogen fixation reduces the need for excessive chemical fertilizers, which can lead to water and atmospheric contamination. Consequently, legumes help to significantly mitigate the environmental impact of cattle farming (Raza et al., 2020). In the Peruvian Amazon, *Centrosema macrocarpum* has proven effective in restoring overgrazed soils. Experiments using degraded pastures of *Urochloa brizantha* to establish agroforestry systems have validated the effectiveness of this legume (Alegre et al., 2017). In the evaluated SPSi, an area of 800 m² (8%) per hectare was established with *Centrosema macrocarpum*.

The shrub used in the SPSi is *Tithonia diversifolia* (commonly known as Botón de Oro), a perennial shrub that can grow between 2 and 5 meters in height (Cook et al., 2020). It is notable for its high potential for dry matter production, its adaptability to a range of climatic and soil conditions, and its high nutritional value, even though it is not a legume (Cook et al., 2020). Empirical evidence has shown that the inclusion of this shrub species is effective for productive cattle management (Castañeda-Álvarez et al., 2016; Rivera et al., 2022). Additionally, studies conducted in tropical conditions with low humidity confirm that supplementing cow diets with small amounts of *Tithonia diversifolia* not only increases milk productivity but also helps mitigate methane (CH₄) emissions (Rivera et al., 2022). In the evaluated SPSi, an area of 1,500 m² (15%) per hectare was established with *Tithonia diversifolia*. This area was arranged in a hedge design consisting of three rows, with a planting distance of 1x1 meter.

The final component of the SPSi consists of timber seedlings. *Erythrina edulis* was used for living fences, planted with a spacing of 5 meters, resulting in 80 plants per hectare. Other species include *Cordia gerascanthus* (Black Laurel, 8-15 years), *Cedrelinga catenaeformis* (Tornillo, 30 years), *Brosimum alicastrum* (Machinga, 8 years), *Vitex pseudolea* (Paliperro, 30 years), *Sauvagesia erecta* (Goma Huayo, 8 years), and *Guazuma crinita* (Bolaina, 5-8 years). These trees are expected to provide 15% to 20% shade per hectare. The native timber seedlings were planted in an area of 500 m² (5%) per hectare, following a design of one row per strip, with a spacing of 20x15 meters and 100 plants per hectare. Many of these species are anticipated to generate income after four to eight years.

The cattle in the system is Girolando, a cross between Holstein (5/8) and Gir (3/8), which has good performance and adaptability in tropical dairy farming and dual-purpose systems, with a weight standard of 450 kg (Perulactea, 2012, 2014). The weight of the calf at weaning is 150 kg, and the annual lactation period is 305 days. Between the traditional system and the SPSi, productivity per cow can vary from 5 to 6.5 liters per day, the calving interval ranges from two to one year, and the carrying capacity is 1 to 2 or 3 tropical livestock units (TLU; 1 TLU = 450kg) with their respective calf per hectare (Durango et al., 2021; Mahecha et al., 2007; MIDAGRI, 2023a; Rivera et al., 2015, 2022, 2023; Rogerio et al., 2017).

3.2. Assumptions for the Discounted Cash Flow Model

As the established trial is still in the evaluation phase, projections of animal response indicators, productivity, costs, and income were made for the economic evaluation—based on expert opinions, scientific literature, commercial data, and official statistics (Durango et al., 2021; Mahecha et al., 2007; MIDAGRI, 2023a; Rivera et al., 2015, 2022, 2023; Rogerio et al., 2017). The analysis period is set for 8 years, from 2023 to 2030, which corresponds to the productive lifespan of the dual-purpose Girolando

cattle used in this evaluation. The discount rate is set at 8% (MEF, 2021). This analysis uses current prices, meaning the cash flow incorporates an adjustment for inflation. This indexation is applied to the entire cost and income structure, using the Consumer Price Index (CPI) as a reference (BCRP, 2023a). The analysis is conducted in U.S. dollars (US\$), with a conversion from Peruvian Soles (PEN) based on the exchange rate at the time of the investment, which was 3.83 PEN per US\$ (BCRP, 2023c). Table 1 synthesizes the technical parameters of the production system.

Table 1. Productive assumptions for building the cash flow per hectare.

Information of the production system	Scenarios			
	Traditional	SPSi PS	SPSi MS	SPSi OS
Milk productivity (l cow ⁻¹ day ⁻¹)	5	6.5	6.5	6.5
Annual lactation period (days)	305	305	305	305
Stocking rate (animals ha ⁻¹)	1	1	2	3
Weight of 1 TLU (kg)	450	450	450	450
Weight of calf at weaning (kg)*	150	150	150	150
Productive lifespan of the system (years)	8	8	8	8

*In the traditional scenario, there is approximately one calf every two years and in the SPsi one every year, respectively. Note: The three scenarios for SPsi are: PS: pessimistic scenario, MS: moderate scenario, and OS: optimistic scenario.

It is important to note that, since there is no significant demand from the dairy industry, quality aspects do not influence the product's value. The economic benefits of implementing an SPsi will stem from higher animal stocking rates (SR), improvements in productivity, increased efficiency in the cost structure, and the sale of timber. Additionally, the analysis accounts for the salvage value of the animals at the end of the evaluation period.

Furthermore, scientific literature evaluating the productive potential of *Urochloa brizantha* and *Tithonia diversifolia* for improving dairy production systems was consulted (Durango et al., 2021; Mahecha et al., 2007; Rivera et al., 2015, 2022; Rogerio et al., 2017). Based on this, it is anticipated that with the SPsi, the stocking rate (SR) will increase from 1 to 2 TLU per hectare, or even, in a more optimistic scenario, to 3 TLU per hectare. Milk productivity is expected to rise from 5 liters per day per cow in the monoculture system to 6.5 liters per day per cow in the SPsi. Finally, regarding beef production, the monoculture system produces one calf at weaning per cow of 150 kg, approximately every two years, whereas in the SPsi, the frequency is projected to increase to one calf per year with the same liveweight.

During the analysis period, no renewal for productive maintenance is assumed for *Urochloa brizantha* in the traditional system, consistent with local management practices, as cost constraints prevent producers from engaging in this practice. Similarly, no renewal is assumed in the SPsi; however, this is due to the efficient land management that makes renewal unnecessary. Additionally, it is important to highlight that only organic fertilizers will be used in the SPsi, which results in cost savings and reduces the burden of fertilizer expenses in the cost structure (Contexto Ganadero, 2023).

3.3. The Discounted Cash Flow Model

The cash flow organizes the income and expenses for the evaluated investment alternatives, resulting in a net benefit for each analyzed period. This enables the calculation of various profitability

measures, which take into account the time value of money by applying a discount rate (Miranda, 2022). As defined by CEPEP (2017), the profitability indicators used in this evaluation include:

The first indicator is Net Present Value (NPV). The NPV is calculated by summing the net benefits derived from the cash flow and discounting them to their present value using the discount rate. If the NPV, as shown in equation (1), is greater than zero, the investment alternative is deemed profitable.

$$NPV = \sum_{t=1}^T \frac{NCF_t}{(1+r)^t} - I_0 \quad (1)$$

where:

I_0 is the initial investment; NCF_t is the net cash flow (difference between income and costs) for each period, and r is the discount rate.

The Internal Rate of Return (IRR) is a specific discount rate (r^*) that makes the NPV of equation (1) equal to zero, as shown in equation (2). If the IRR is greater than the discount rate, it indicates profitability.

$$NPV = 0 \quad (2)$$

The third indicator is the benefit-cost ratio (BC). It is calculated as the ratio between the present value of benefits (PVB) and the present value of costs (PVC), as shown in equation (3). The discount rate is applied to both the PVB and PVC in this calculation. If the PVB exceeds the PVC, the investment is considered profitable. In other words, for profitability to be indicated, the BC from equation (3) must be greater than one.

$$BC = \frac{PVB}{PVC} \quad (3)$$

The fourth indicator is the payback period (PB). This indicator reflects the time it takes to recover the initial investment (I_0) in the productive project. It indicates the moment when the cumulative net cash flows equal the initial outlay. When comparing various investment alternatives, the preferred option is the one with the highest NPV, IRR, and BC, while also having the lowest PB, as it implies faster recovery of the investment.

3.4. Risk Analysis

Agricultural ventures, like any other productive projects, are subject to various elements of risk and uncertainty. Climatic factors, fluctuations in input prices, or changes in market prices for end products can all affect profitability and are typically beyond the control of the producer. A comprehensive economic evaluation should incorporate these potential risks to provide a more realistic perspective on the expected outcomes. Studies that account for these factors allow for a more accurate estimation of benefits (Choudhary et al., 2016; Vilani et al., 2024).

In line with this approach, and to complement the analysis, Monte Carlo simulations were conducted to generate probability distributions for key profitability indicators such as NPV and IRR. This approach allows for the calculation of expected values for these indicators. According to the law of large numbers, this is the most accurate estimator. Additionally, variability measures, such as the coefficient of variation, can be used to obtain probability values (Park, 2007). The simulations were performed using @Risk software, with a 90% confidence level and 5,000 iterations.

Based on scientific literature (Durango et al., 2021; Mahecha et al., 2007; Rivera et al., 2015, 2022; Rogerio et al., 2017), minimum, most likely, and maximum values were identified for the variables of interest, enabling the use of the Pert distribution (Park, 2007). The details of the values for the moderate scenario are shown in Table 2. The pessimistic and optimistic scenarios have the same variability applied here.

Table 2. Parameters for Pert Distribution, moderate case, per hectare.

Variable	Minimum	Most likely	Maximum
Milk price (US\$ l ⁻¹)	0.32	0.34	0.36
Milk productivity (l cow ⁻¹)	6.2	6.5	6.8
Stocking rate (cows ha ⁻¹)	1	2	3
Discount rate (%)	7.6	8.0	8.4

This analysis was carried out for four different scenarios. The first scenario represents the traditional monoculture system using *Urochloa brizantha* cv. Marandú (Traditional system). The second scenario represents the SPSi with all its productive benefits but assumes a pessimistic expectation of only 1.2 TLU per hectare (SPSi PS). The third scenario represents a moderate outcome, assuming 2 TLU per hectare (SPSi MS). Finally, the fourth scenario assumes an optimistic outcome with 3 TLU per hectare (SPSi OS). Milk productivity is also expected to rise, with an average increase from 5 liters per day in the traditional system to 6 liters per day in the SPSi.

4. Results

4.1. Cost and Revenue Structure

Commercial information on the costs of productive systems per hectare is available. Although the data is not broken down in extensive detail, it is sufficient to consolidate the total costs for both establishment (CE) and operational expenses (CO). The CE refers to the initial investments required to set up the productive system, amounting to US\$3,055 per hectare. Of this total, cattle acquisition accounted for 51.3%, equivalent to US\$1,567. The remaining 48.7%, or US\$1,488, was allocated to land preparation, which includes clearing and burning (US\$522), fencing (US\$783), and planting (US\$183). Overall, the two systems—traditional and SPSi—have similar CE, with higher costs in the traditional system due to its reliance on chemical fertilizers, amounting to US\$157 and to other infrastructure items that make it more costly. Table 3 provides more detail on the cost and income structure.

Table 3. Financial assumptions for building the cash flow per hectare.

Variables	Traditional	SPSi PS	SPSi MS	SPSi OS
Milk price (US\$ l ⁻¹)	0.34	0.34	0.34	0.34
Beef price (US\$ kg liveweight ⁻¹)	1.54	1.54	1.54	1.54
Animal acquisition (US\$ animal ⁻¹)	1,567	1,567	1,567	1,567
Clearing, burning, and others*	522	-	-	-
Chemical fertilizers*	157	-	-	-
Fencing	783	783	783	783
Planting	183	183	183	183
Management cost (US\$ cow ⁻¹ y ⁻¹)	261	418	418	418
Annual income from milk sales (US\$ TLU ⁻¹)	518	673	673	673
Annual income from beef sales (US\$ calf ⁻¹)**	232	232	232	232

*Not applicable for the SPSi.; **In the traditional scenario, sales occur every two years.

On the other hand, CO refers to the annual expenses necessary to maintain the system, including inputs and animal health care. These operational costs are US\$418 for the SPSi and US\$261 for the

traditional system. Labor costs are implicitly included within these figures. Neither the traditional nor the SPSi systems incur costs related to pasture renewal.

Regarding market conditions, the price of beef is US\$1.54 per kg liveweight (INEGI, 2023), which reflects the value for selling a weaned calf weighing approximately 150 kg at US\$231. The price of milk in the region is US\$0.34 per liter. As a result, revenues in the first year of operation could reach up to US\$1,028 for the traditional system, while in the SPSi scenarios, they could range from US\$2,714 to US\$6,333, depending on varying projections of milk productivity and stocking rates.

4.2. Profitability Indicators

The profitability indicators presented in Table 4 clearly demonstrate that all analyzed scenarios are profitable, as the NPV is greater than zero, and the IRR exceeds the market discount rate across all cases. However, there is a significant difference between the traditional system and the SPSi scenarios. The NPV increases from a modest US\$61 in the traditional system to values ranging from US\$9,564 to US\$20,465 in the SPSi scenarios. Similarly, the IRR shows a substantial improvement, rising from 8.17% in the traditional system to 26.63%, 29.02%, and 30.33% in the various SPSi scenarios. These results underscore the economic advantages of adopting the proposed SPSi over the traditional monoculture system.

Table 4. Profitability indicators.

Indicator	Traditional	SPSi PS	SPSi MS	SPSi OS
NPV (US\$)	61	9,564	15,014	20,465
IRR (%)	8.17	26.63	29.02	30.33
BC	1.006	1.628	1.632	1.634
PB (years)	7.98	5.78	4.91	4.55

Notes: The discount rate is 8% and the evaluation is for 2.5 hectares.

The BC ratio follows the same trend, consistently exceeding a value of 1 and increasing according to the expectations of each scenario. The payback period is approximately 7.98 years for the traditional system, while in the SPSi scenarios, it ranges from 5.8 to 4.5 years, demonstrating a quicker recovery of the initial investment in the silvo-pastoral systems.

To account for the inherent risk and uncertainty, a probabilistic analysis using Monte Carlo simulation was applied. This approach allows for more robust estimates by associating probability distributions with key indicators. Given the productive context of this evaluation, stocking rate (SR) and milk productivity (MP) were selected as the primary determinants of profitability. For these variables, minimum, most probable, and maximum values were obtained, which enabled the use of the Pert distribution. The analyzed indicators—NPV and IRR—confirmed profitability across all scenarios.

As indicated in Table 5, the highest average NPV was observed in the optimistic scenario, with a value of US\$20,455, followed by the moderate scenario with US\$15,021. The average IRR in these systems was 30.33% and 29.03%, respectively. In contrast, the traditional system displayed a coefficient of variation (CV) of 4.4. The three SPSi scenarios exhibited improved precision in the estimations, with a lower CV ranging from 0.0303 to 0.0333, indicating more reliable profitability predictions under the SPSi models.

Table 5. Quantitative risk analysis.

Indicator	Measure	Traditional	SPSi PS	SPSi MS	SPSi OS
NPV	Mean (US\$)	33	9,555	15,021	20,455
	SD*	144.34	289.85	486.07	680.53
	CV**	4.3726	0.0303	0.0324	0.0333
	Prob(NPV<0)***	0.41	0.00	0.00	0.00
IRR	Mean (%)	8.09	26.62	29.03	30.33

*SD: Standard deviation; **CV: Confindece Interval; ***Prob: Probability.

In Figure 1, the differences among the four technologies can be better observed. The probability distribution for the traditional system (red) is profitable; however, it is the one positioned furthest to the left. The SPsi shifts the NPV curves to the right, in line with increases in MP and SR, across the pessimistic (blue), moderate (green), and optimistic (purple) scenarios. As a result, the average NPV value increases from US\$33 to values between US\$9,555 and US\$20,455.

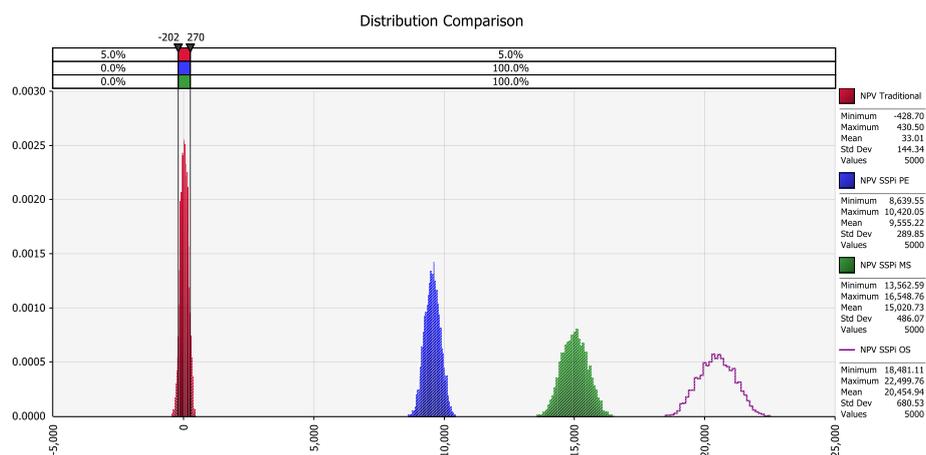
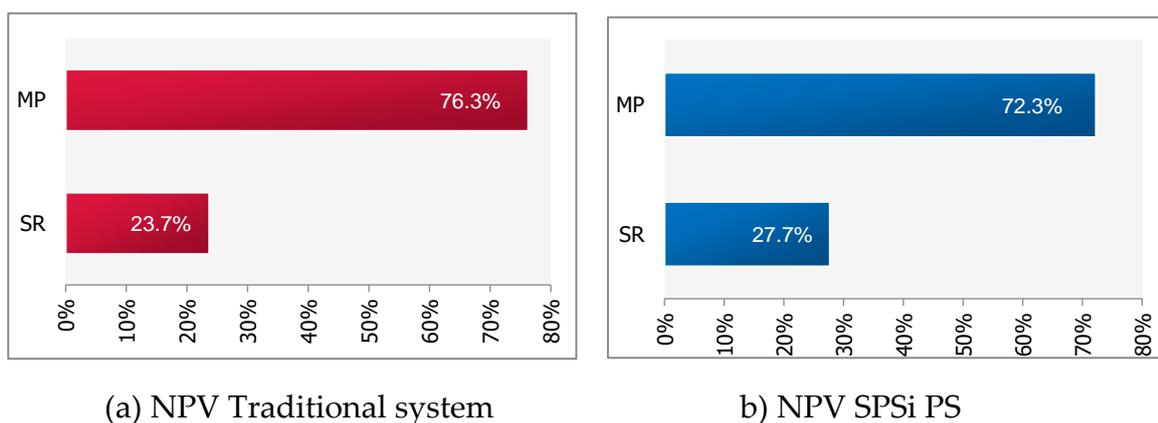


Figure 1. NPV probability distributions by analyzed scenarios.

To verify and explore the influence of factors underlying profitability, a sensitivity analysis was conducted. Specifically, the contribution to variance quantifies the impact of certain variables on the Net Present Value (NPV). The results of this analysis are visualized in the form of tornado charts, which are presented in Figure 2.



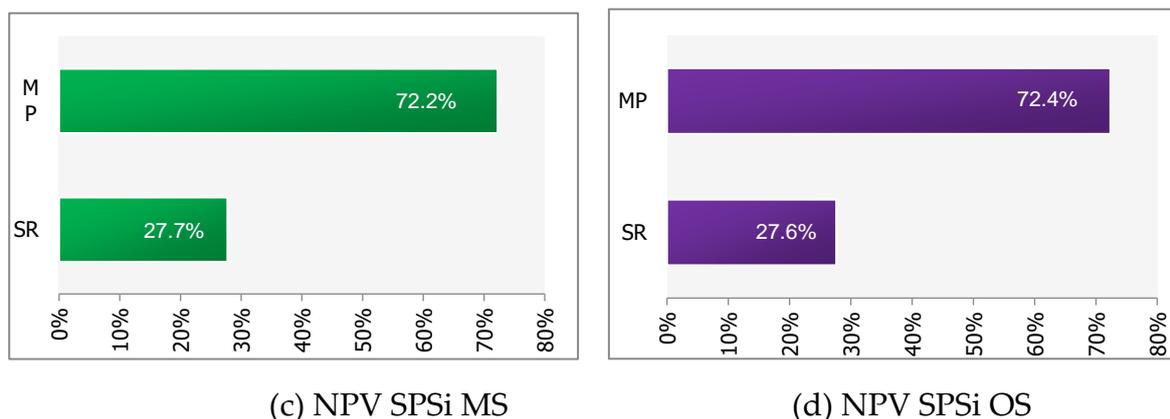


Figure 2. NPV sensitivity analysis – contribution to variance.

The variable with the greatest influence on profitability is milk production. In the traditional system, MP accounts for 76.3% of the variation in NPV, while in the SPSi scenarios, it accounts for 72.3%, 72.2%, and 72.4% in the pessimistic, moderate, and optimistic scenarios, respectively. This result was derived from a sensitivity analysis conducted using Monte Carlo simulation with a 90% confidence level. Since market prices cannot be influenced directly by producers, MP becomes the most important determinant for enhancing economic benefits across all systems. The second most significant variable is stocking rate, which explains 23.7% of the variation in NPV in the traditional system. In the SPSi scenarios, SR contributes an average of 27.7% to the variation in NPV. This indicates that SR plays a crucial role in the financial performance of the SPSi, alongside MP. Thus, optimizing both MP and SR is key to maximizing profitability in these systems.

5. Discussion

5.1. Economic Evaluation of SPSi in San Martín Province

SPS are increasingly recognized by policy and the beef and dairy value chains as effective alternatives for improving the technical, economic, and environmental aspects of cattle farming (Cubbage et al., 2012; Mavisoy et al., 2024; Moreno Lerma et al., 2022, 2023; Díaz Baca et al., 2024). The findings of this study strongly underscore the financial and environmental benefits of implementing intensive silvo-pastoral systems (SPSi) in the San Martín region of Peru over traditional grass monoculture systems. Across various scenarios, SPSi consistently outperformed the traditional systems, showing marked improvements in key financial metrics such as NPV, IRR, and BC ratio. The results not only validate the economic potential of SPSi but also align with global evidence from other regions where SPS have significantly enhanced agricultural profitability and sustainability.

The projections in our study show a 30% increase in milk production and a 50% to 250% rise in animal stocking rates per hectare in the SPSi compared to the traditional grass monoculture system. These improvements translate into significant economic benefits. In the evaluated traditional system, the NPV was a modest US\$61, barely above zero, signaling limited profitability. In contrast, the SPSi scenarios showed strong improvements in NPV, ranging from US\$9,564 in the pessimistic scenario to US\$20,465 in the optimistic scenario. This represents an increase of more than 150-fold compared to the traditional system, highlighting the substantial economic advantages of adopting SPSi. Similarly, the IRR increased from 8.17% in the traditional system to between 26.63% and 30.33% in the SPSi scenarios, reflecting significantly higher returns on investment. The BC ratio also increased from 1.006 in the traditional system to values between 1.628 and 1.634 in the SPSi scenarios, signaling a more efficient allocation of resources and a higher return on every dollar invested. The payback period for the traditional system was nearly 8 years, a considerable recovery time for initial

investments. However, SPSi shortened this payback period to between 4.5 and 5.8 years, underscoring the quicker return on investment associated with SPS.

Although SPS are not yet widely known in the study area, another recent analysis in the Peruvian Amazon suggest their profitability: Chizmar et al. (2020) conducted a profitability analysis using the Land Expectation Value (LEV) method for a 10-hectare farm with *Eucalyptus globulus* trees and Holstein cattle. The LEV per hectare was US\$9,272, US\$4,737, and US\$3,230 at discount rates of 4%, 8%, and 12%, respectively. Our results contribute to these findings and help in amplifying the portfolio of economically viable SPS options for this region in Peru.

Our results are also consistent with empirical evidence from other regions around the world, where SPS have demonstrated similar economic benefits. For example, in India, Islam et al. (2022) conducted a study in the Himalayas, which examined the establishment of a SPS on 184 hectares aimed at reducing reliance on forest forage. Through surveys of 222 households across five villages, the study calculated economic indicators for an agroforestry strategy using multipurpose species such as *Amorpha fruticosa*, *Andropogon virginicus*, *Avena sativa*, and *Cytisus scoparius*. The results showed an exceptionally high IRR of 155.73% over a 12-year horizon, driven by improved livestock productivity and sustainable land use practices. While the IRR in our study did not reach this level, the increase to over 30% in the optimistic SPSi scenario still reflects the significant financial advantages of SPSi, especially when compared to the 8.17% observed in the traditional system.

In Brazil, a global leader in cattle production, similar successes with SPS have been documented. Marques Filho et al. (2017) reported that an SPS on 120 hectares, featuring *Urochloa brizantha* cv. Marandú and *Eucalyptus* trees, achieved returns of 12% to 120% over three years, compared to returns ranging from -10% to 44% in traditional systems. The high variability in returns across traditional systems was due to factors such as poor soil management, climate variability, and the high costs of chemical inputs—issues that SPS help mitigate. Our study shows that in the San Martín region, the SPSi similarly outperformed traditional systems by reducing reliance on chemical fertilizers and improving soil health through the integration of legumes and trees. Another study in Rio Grande do Sul, Brazil, analyzed a 2-hectare SPS with ryegrass and *Eucalyptus grandis* trees. With trees planted at a density of 166 per hectare and four years old, the system showed profitability with an IRR of 19.79% (Bernardy et al., 2022).

In Costa Rica, a study by Jiménez-Ferrer et al. (2015) evaluated an SPS with *Erythrina poeppigiana* shrubs and dairy cows, yielding positive net margins in milk production. In Mexico, an evaluation of an SPSi with 60 Gyr cattle on 58 hectares showed a positive net margin per cow of US\$109.4 (Estrada López et al., 2018).

Further comparisons can be drawn from studies in Colombia. Sandoval et al. (2023) conducted a financial analysis comparing two SPS—*Urochloa brizantha* cv. Toledo + *Leucaena leucocephala* and *Urochloa* hybrid cv. Cayman + *Leucaena leucocephala*—with two monoculture grass systems. Their analysis revealed that although SPS establishment costs were higher, the systems showed superior animal performance, with 33% higher stocking rates, 51% greater daily liveweight gains, and a 34% increase in annual beef sales income. These results align closely with our findings, where the stocking rates in SPSi scenarios were projected to increase by up to 250%, and milk productivity was expected to rise from 5 liters per cow per day in the traditional system to 6.5 liters in the SPSi scenarios. This increased productivity directly translates into greater revenues, with the first-year revenues for the SPSi ranging from US\$2,714 to US\$6,333, compared to just US\$1,028 in the traditional system.

Moreover, Enciso et al. (2019) conducted an economic analysis in Colombia comparing a grass monoculture system—*Urochloa* hybrid cv. Cayman—with a silvopastoral system that integrated *Urochloa* hybrid cv. Cayman and *Leucaena diversifolia*. Despite the SPS having 60% higher establishment costs, it delivered a 66% increase in gross income per hectare and a 119% increase in net income. In our study, the establishment costs for SPSi were estimated at US\$3,055 per hectare, nearly identical to the traditional system. However, the operational costs for the SPSi were slightly higher at US\$418 per hectare per year, compared to US\$261 for the traditional system. These additional costs were offset by the higher revenues from milk and beef production, as well as the

long-term cost savings from reduced reliance on chemical fertilizers and enhanced land productivity. Enciso et al. (2019) also found that the evaluated SPS reduced the minimum land area required to generate two Colombian basic salaries from 6.54 hectares to 3.76 hectares and shortened the payback period from 6 years to 4 years. Their risk analysis highlighted a 72% probability of economic loss for the monoculture system, whereas the SPS reduced this risk to 0%. Sensitivity analysis identified that the sale price per kilogram of live weight and animal production were the main drivers of profitability, accounting for 64.2% of the variance in the monoculture and 55.2% in the SPS. Stress tests revealed that negative changes in these factors could reduce the NPV of the monoculture by 335%, compared to only a 57% reduction for the SPS, underscoring the SPS's financial viability and greater resilience compared to the monoculture system. These results are also consistent with our evaluation, i.e., with the estimated reduction in the payback period from 8 to 4.5-5.8 years, the reduction of the risk of economic loss from 41% to 0%, and the dependence on the end product prices (in our case milk) on economic viability.

In a case study, Gonzalez Quintero et al. (2024) evaluated the implementation of SPS on four dairy farms in Colombia. Their findings showed that the introduction of improved pasture management and SPS helped mitigate the losses that the traditional system was incurring, though it did not immediately lead to profitability. Improved pasture management, rotational grazing, and optimized fertilization resulted in higher milk production, but these gains were insufficient to fully cover costs in the initial phases. However, as stocking rates increased and the areas of improved pastures expanded in subsequent scenarios, economic indicators such as NPV, IRR, and BC ratio showed improvement, suggesting the potential for profitability with sustained investment and enhanced management practices – similar to our results for the different SPSi scenarios.

One of the primary advantages of SPS is their ability to diversify income streams, particularly through timber production. In our study, timber production was projected to increase profitability by 2.06% to 4.64%. Rade et al. (2017) in Ecuador showed that integrating *Jatropha curcas* into a livestock system as a living fence for biofuel production resulted in an 18% return on investment. The inclusion of timber and other agroforestry components in SPS not only provides additional revenue sources but also contributes to environmental sustainability, a critical consideration in regions facing deforestation and soil degradation.

Another key benefit and potential income stream of SPS, though not factored into this study's financial analysis, is the potential for payments for ecosystem services (PES), particularly for carbon sequestration. Studies have shown that SPS significantly reduce greenhouse gas emissions. For instance, Sandoval et al. (2023) found that SPS reduced methane emissions by 0.03 grams per gram of liveweight gain, translating to an annual reduction of 145 tons of CO_{2eq} for a herd of 1,000 cattle. This reduction in emissions has the potential to generate substantial income through carbon credits. In their study, Sandoval et al. calculated that these reductions could be valued at US\$6,122 per year based on an average price of US\$42.25 per ton of CO_{2eq}. Similarly, Gonzalez Quintero et al. (2024) found that SPS could mitigate up to 163 tons of CO_{2eq}, valued at US\$27,716, while also improving financial metrics such as NPV, IRR, and BC ratio. Furthermore, the SPS treatments provided substantial microclimatic benefits, with over 60% shade coverage. Replacing this natural shade with synthetic structures would cost US\$12,158 over three years, but natural shade saves US\$4,053 annually, translating to an economic value of over US\$2 million per year if applied to a 1,000-hectare system. They also found that including the environmental benefits of CH₄ reduction in the financial analysis significantly enhanced the financial indicators of the SPS. Similarly, Gonzalez Quintero et al. (2024), in their case study on enhancing dairy systems in Colombia, demonstrated that improved pasture management and the implementation of SPS can mitigate up to 163 tons of CO_{2eq}, valued at US\$27,716, while also improving financial metrics such as NPV, IRR, and BC ratio.

In summary, empirical evidence from both large- and small-scale trials supports the profitability of SPS, with returns ranging from 12% to 156%. In many cases, these returns exceed those calculated in this study, which range from 26.62% to 30.33%. Variations in investment returns can be attributed to cattle farming's sensitivity to environmental, market, and institutional factors across different

regions (Helguera Pereda & Lanfranco Crespo, 2006). Nonetheless, profitability in SPS has consistently been demonstrated, and the results of this analysis, combined with the regional context, indicate a favorable environment for adopting an SPSi in San Martín Province in Peru.

5.2. *Obstacles and Chances for Scaling the Adoption of SPS*

The adoption of SPS faces a range of significant barriers that must be addressed to facilitate widespread uptake. These challenges include: (i) financial constraints, such as limited access to credit and lengthy payback periods, which can deter farmers from making long-term investments; (ii) knowledge and information gaps, including insufficient technical assistance and extension services, and the need for specialized skills to implement SPS practices; (iii) socio-cultural factors, such as entrenched gender roles and the prevalence of traditional cattle practices like extensive grazing on natural pastures, which may hinder the shift to more sustainable systems; (iv) labor shortages, exacerbated by competition with more lucrative (and sometimes illegal) sectors, which reduce the available workforce for agricultural activities; (v) unclear land tenure, which discourages long-term investments in land improvements; (vi) market dynamics, such as fluctuating prices for inputs and end products; (vii) legal restrictions, which may limit the ability of farmers to fully utilize these systems; and (viii) farmers' inherent risk aversion, which leads to reluctance in adopting new technologies due to fear of potential losses (Sandoval et al., 2023; Enciso et al., 2022; Tschopp et al., 2020, 2022; Jara-Rojas et al., 2020; Lee et al., 2020; Charry et al., 2019; Puppo et al., 2018; Raes et al., 2017; Zepeda Cancino et al., 2016; Zapata et al., 2015; Calle et al., 2013).

To overcome these multifaceted obstacles, a comprehensive and integrated approach is necessary. This includes targeted interventions, such as providing access to favorable agricultural credit with flexible terms and designing government programs that specifically focus on reducing emissions in cattle farming. It is equally important to ensure that the environmental benefits, such as the mitigation of greenhouse gas emissions achieved through SPS, are financially recognized. This can be accomplished by enabling producers to participate in PES schemes or carbon markets, which would reward their contributions to climate change mitigation (Díaz et al., 2019).

While the benefits of scaling up SPS are considerable, it is essential to recognize potential unintended consequences that may arise from widespread adoption. Parodi et al. (2023) emphasize that SPS should be implemented primarily in areas unsuitable for crop production to prevent competition with other agricultural systems. However, this approach may result in unintended negative outcomes, such as increased deforestation, particularly when cattle intensification occurs on marginal lands and land tenure is unclear (Castro-Nuñez et al., 2021).

One concern is that improved cattle birth rates within SPS can lead to surplus calves, which are often sold to unsustainable fattening operations located at deforestation frontiers. In fact, cattle farming is one of the leading drivers of deforestation in Colombia and Latin America (Castro-Nuñez et al., 2021; Calle et al., 2013; Zapata et al., 2015). Additionally, the productivity gains associated with SPS could encourage farmers to expand operations into forests and other ecosystems, a phenomenon known as the Jevons paradox (Alcott, 2005).

To address these risks, a combination of incentives and robust monitoring mechanisms is necessary to ensure that SPS promote sustainability rather than contribute to deforestation. Effective strategies may include deforestation monitoring, traceability systems, and taxes on conventional pasture use. By implementing these measures, the expansion of SPS can be aligned with sustainable cattle farming goals, mitigating potential environmental harm (Calle et al., 2013; Tschopp et al., 2020).

Conclusions and Recommendations

Our study demonstrates that SPSi provide clear economic and environmental advantages over traditional monoculture grass systems in San Martín, Peru. These systems significantly improve farm profitability by enhancing milk production and increasing animal stocking rates, while also shortening the time required to recover initial investments. In addition to financial benefits, SPSi offer notable environmental gains, such as improved soil health and reduced greenhouse gas emissions,

positioning them as a sustainable solution for cattle farming in the region. These findings align with global evidence, reinforcing the potential of SPSi to increase agricultural productivity and sustainability.

Despite the evident advantages, the adoption of SPSi faces several barriers, including financial constraints, knowledge gaps, and socio-cultural challenges. Addressing these obstacles through targeted interventions, such as improved access to credit and technical support, will be essential to facilitate broader adoption. Overall, SPSi present a compelling model for sustainable cattle farming, offering both economic resilience and environmental benefits. However, ensuring long-term success will require coordinated efforts to overcome adoption barriers and implement supportive policies.

Based on our study we provide the following recommendations:

The wider adoption of SPS should be encouraged: The economic and environmental benefits of SPS demonstrated in this study provide a strong case for promoting these systems across San Martín and other regions. Governmental and non-governmental organizations should prioritize extending SPS to cattle farmers to improve farm profitability and sustainability.

Financial and knowledge barriers need to be addressed for encouraging wider adoption: To accelerate the adoption of SPS, access to favorable credit terms and financial incentives should be provided. Additionally, capacity-building initiatives, technical assistance, and extension services are necessary to bridge knowledge gaps and equip farmers with the skills required to implement and manage these systems.

PES schemes should be implemented: Governments should create frameworks to compensate farmers for the environmental benefits provided by SPS, such as carbon sequestration. Establishing participation in carbon markets or PES programs would generate an additional income stream, encouraging farmers to adopt and sustain these systems.

Unintended consequences of adoption need to be mitigated: While SPS offer numerous advantages, it is essential to prevent potential unintended consequences like deforestation, particularly in regions with unclear land tenure. Policymakers should implement robust monitoring systems, traceability protocols, and deforestation prevention measures to ensure that the expansion of SPS aligns with sustainable land management practices and existing policy frameworks.

Sustainable land management should be fostered through policy interventions: A combination of regulatory mechanisms, including taxes on conventional monoculture pasture use and incentives for sustainable practices, will be crucial to ensuring that SPS contribute to long-term environmental and economic sustainability in Peru's cattle sector.

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data availability statement: The data analyzed in this study is subject to the following licenses/restrictions: Requests to access these datasets should be directed to the corresponding author.

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