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Biotechnical, economic, and environmental assessment of dairy systems in the Peruvian Amazon utilizing the CLEANED tool

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Abstract Silvopastoral systems have been proposed as a sustainable alternative for climate change mitigation, but quantitative information comparing with other systems is limited. This study aimed to evaluate the biotechnical, economic, and environmental impacts of conventional dairy production systems (CPS) and silvopastoral systems (SPS) in San Martin, Peru, using the CLEANED modeling tool. Notably, CLEANED does not explicitly model tree presence on farms. However, after downloading the tool, it was possible to model and precompute each farm's characteristics based on input data, considering the exploitation mode outside the tool's standard scope. This adaptation represents a significant contribution, showcasing how CLEANED can be tailored to evaluate SPS effectively. The analysis focused on methane (CH_4) and nitrous oxide (N_2O) emissions, water use per kg of product, changes in carbon storage, and economic performance. Silvopastoral systems had 3.63 kg CO_2-eq/kg fat and protein-corrected milk (FPCM) lower emissions for CH_4, 0.28 kg CO_2 eq/kg FPCM lower for N_2O, reduced water consumption (24 m^3/kg protein produced) ($P < 0.05$), and higher carbon storage (3.48 t CO_2-eq/ha/year) ($P < 0.05$) than CPS. Conventional systems derived 85% of income from milk sales, while SPS generated 70% from milk, with additional income from live animal sales (20%), wood (6%), firewood (3%),

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and other activities (1%). Silvopastoral systems were more profitable ($493/farm/month) than CPS ($247/farm/month). The study concluded that SPS are more sustainable due to better water use efficiency, higher profitability, and lower GHG emissions, recommending their broader adoption to increase profits and reduce environmental impacts.

Keywords Profitability · Cattle management · Methane · Nitrous oxide · Carbon · Silvopastoralism

Introduction

The global demand for food production has been steadily rising, primarily driven by population growth. Consequently, agroecosystems are under increased strain to fulfill these requirements. In the context of developing countries that rely predominantly on small-scale farming and animal husbandry, this predicament becomes even more dire as they are very susceptible to the impacts of climate change (Descheemaeker et al. 2016).

Livestock systems in the Peruvian Amazon are mainly classified as extensive involving the continuous grazing of wide regions with low stocking density and a lack of proper system management. These regions in the Peruvian Amazon typically consist of natural pastures or introduced species that have been degraded or are currently undergoing deterioration. In Peru, the sectors of land use change and forestry and other activities account for 86.5% of greenhouse gas (GHG) emissions, while agriculture contributes 13.5%, with 7.3% originating from enteric fermentation, 3.2% from direct emissions of N_2O from the soil, and 3% from other activities (MINAM, 2023).

Silvopastoral systems (SPS) have been proposed as alternatives to conventional livestock systems to increase diversity, perenniality, and resilience of production in face of climate change (Picasso and Pizarro 2024). In the Amazon region of Peru, there are two types of livestock systems: traditional extensive systems without trees, and systems with dispersed trees such as guava (*Inga edulis)*, bolaina (*Guazuma ulmifolia*), paliperro (*Barbeyana cogniaux*), and shrub species as erythrina (*Erythrina poeppiagiana*) (Fuentes et al. 2022). While certain systems may have trees, only a limited number of them truly qualify as silvopastoral systems. These systems consist of grasslands with trees that are either widely spaced or planted in groups throughout the grassland. The purpose of these trees is to offer shelter to animals and enhance livestock feeding by providing forage (Navarro et al. 2023).

Thus, based on substantial scientific evidence from pilot studies conducted on areas ranging from 0.5 to 1 hectare, it is clear that implementing SPS in Peru and other countries as Colombia, Brazil and Ecuador has proven to be advantageous (Enciso et al. 2022; Fuentes et al. 2022; Munaro et al. 2023; Torres et al. 2022). Diverse technology techniques have enabled the assessment of livestock systems in terms of their environmental consequences and profitability, according to the circumstances of the producer and taking into account the overall land area utilized for livestock operations. The assessment instrument CLEANED (Comprehensive Livestock Environmental Assessment for Improved Nutrition, a Secured Environment and Sustainable Development along Livestock Value Chains) simulates the effects of alterations in cattle production systems and value chains over different routes on land utilization, productivity, economic factors, water consequences, GHG emissions, and soil well-being (Notenbaert et al. 2021).

We hypothesize that the use of a modeling tool would allow assessing the advantages of SPS in productive, socioeconomic, and environmental sustainability compared to current livestock systems in the high tropics of the San Martin region. The aim of this study was to assess the biotechnical, economic, and environmental effects of conventional pastoral systems (CPS) and SPS in the San Martin region of Peru, during both the dry and rainy seasons. The evaluation was conducted using the CLEANED modeling tool, which has previously been utilized for similar analyses in other developing countries including Ecuador, Ethiopia, Kenya, Nicaragua, Tanzania, Tunisia, and Vietnam (Pfeifer et al. 2018).

Materials and methods

Site description

The research was conducted in the Cuñumbuque district, situated in the San Martín amazon region of Peru. During data collection (January–December, 2022), temperature, relative humidity, and

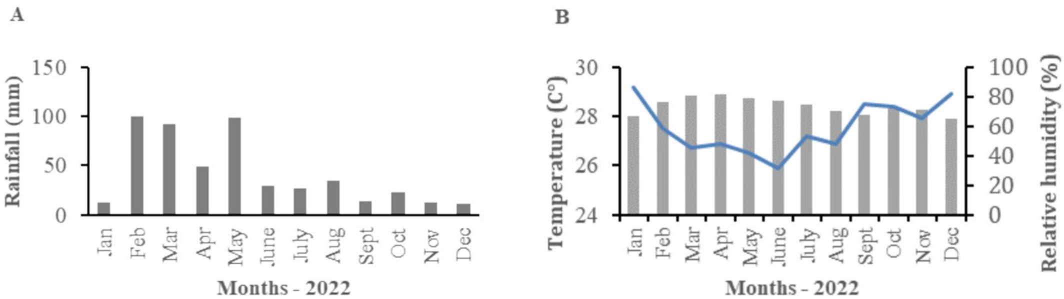

Fig. 1 Monthly measurements of precipitation, temperature, and relative humidity in the San Martín region were recorded during the year of data collection. *Source* SENAMHI (2023). **A** Rainfall, **B** Temperature and Relative humidity

precipitation average were 28 °C, 73% and 42 mm, respectively (Fig. 1; SENAMHI, 2023).

The livestock systems shared several common features, including: the herd's genotype, which primarily consisted of a crossbreed of Gyr, Holstein, Jersey, Brown Swiss, Brahman, and other breeds; the utilization of *Brachiaria brizantha* grass varieties Marandú, Xaraés, and the *Brachiaria* hybrid Mulato as the primary forage source; and the incorporation of supplements containing varying proportions of rice polishing, corn, soybean meal, mineral mixture, and fish meal. Within SPS, the inclusion of gliricidia (*Gliricidia sepium*) and erythrina (*Erythrina poeppigiana*) is noted for the purpose of leaf browsing. Additionally, trees such as guava (*Inga edulis*), bolaina (*Guazuma ulmifolia*), and paliperro (*Barbeyana cogniaux*) are also present in these systems.

Data collection and utilization of CLEANED

The study was carried out in accordance with the guidelines and regulations from Institutional Animal Care and Use Committee (IACUC) of the National Agrarian University, protocoled TR.No.0185-2016-CU-UNALM. A total of 20 farmers, comprising 10 CPS and 10 SPS, were chosen at random from a preselection list consisting of 72 farmers. This list was compiled based on field visits to livestock systems and Cuñumbuque Cattlemen association.

The 20 farms evaluated had a single grass species, *Brachiaria brizantha*, with variations only in the cultivar type on each farm. The criteria for classifying systems as SPS or CPS were primarily based on the percentage of tree cover in the total area of the farm dedicated to animal production. Farms with less than 15% tree cover were classified as CPS, while those with more than 15% were classified as SPS. Additionally, the benefits that producers gained from the interaction between trees and grazing were evaluated, such as providing shade for the animals, harvesting fruits, firewood, or timber, and the role of the trees in preventing the need for permanent post replacement in fences. Producers who reported more than three benefits in the surveys were classified as SPS, in addition to having more than 15% tree cover.

Furthermore, a thorough assessment of the farms was conducted, which involved identifying key productivity indicators and gathering samples of both fodder and milk. The milk samples were evaluated on-site using the LACTOSCAN SP (Ultrasonic Milk Analyzer SP60, China) portable analyzer. Only forage biomass was evaluated using the quadrant method, and the result was entered into the CLEANED tool.

This tool is a static model designed to assess the environmental impacts of livestock enterprises annually. Developed using Microsoft Excel 2016, it facilitates quick, preliminary impact assessments with minimal data input. The model evaluates all inputs required to support the livestock, such as feed and feed crop residues, but does not account for the entire farm area or crops not used for feeding the animals (Mukiri et al. 2019). The data collected on farm characteristics, production, and the nutritional value of the system's products during both the dry and rainy seasons were entered into the spreadsheets of the CLEANED X Tool Version 3.0.1 (Notenbaert et al. 2021).

To enable the tool to model production variables, water footprint, carbon stock, and GHG emissions, information was collected regarding general aspects of the farm, such as the number of dry and rainy season days; data on the livestock, including the total number of animals and by category, live weight, and milk production; and information related to manure management, such as inputs and outputs, quantities of liquid and solid storage, and amounts used for fuel, fertilizer, and other purposes. Information was also gathered on the feeding of the herd in different seasons of the year, including the type and amount of forage available. Additionally, data was obtained on the farm's food production, including crop management, types of crops and trees, quantity, type, and costs of fertilizers used.

It is important to note that the CLEANED tool, in its standard configuration, does not explicitly model the presence of trees on the farm. However, after downloading the tool, it was possible to model and precompute the specific characteristics of each farm based on the input data for CLEANED, taking into account the exploitation mode "outside" of the modeling tool. This is a key contribution of the present study, as it demonstrates how to use CLEANED to evaluate SPS through proper configuration and entry of the relevant information. The tool modeled various response variables, including the amount of land required for livestock activity (pasture area ha/year), emissions of methane (CH_4) and nitrous oxide (N_2O) expressed in t CO_2-eq/ha/year and kg of CO_2-eq/kg of fat- and protein-corrected milk (FPCM), water use per kilogram of product (m^3/kg protein), and changes in carbon storage (t CO_2 eq/ha/year) for each livestock system.

The estimation of GHG emissions considered enteric fermentation, the use of manure, and land management as sources of emissions. These sources were evaluated using the criteria defined by Tier 2 for methane and Tier 1 for nitrous oxide of the IPCC methodology, as outlined by Hergoualc'h et al. (2019). The economic analysis conducted was a cash flow type analysis, derived by assessing the annual incomes and expenditures, ultimately yielding the profit in US dollars. The total income was derived from the aggregate of milk sales per farm per year and animal sales per category. The expenses were derived from both investments, such as land, machinery and equipment, vehicles, facilities and civil works, pastures, and animals, as well as operational costs, including labor, supplementary food, materials and supplies, third-party services, equipment maintenance and repair, and depreciation. The profit (US dollars/farm/year) was obtained from the total expenses and income of the farms. For this study, net benefits were not calculated.

Statistical data analysis

The statistical model used by the tool is deterministic, as it predicts outcomes based on a specific set of initial conditions and parameters. This means that the model produces results without incorporating randomness or inherent variability in its predictions. The statistical analysis of the CLEANED data was conducted using the SAS program (version 9.4., SAS Inst., Cary, NC). The normal distribution was tested using the Shapiro–Wilk tests. The means of the quantitative data that followed a normal distribution were compared using a student's t-test (parametric tests), using both the confidence interval estimation analysis and the t-score probability hypothesis testing method for two independent sample groups.

Table 1 Attributes (means ± SD) of dairy farms in the San Martin region

Category	Parameter	CPS	SPS
Production	Head (Units)	58 ± 24	83 ± 47
	Cow in production (Units)	24 ± 11	26 ± 13
	Total area (ha)	42 ± 25	53 ± 33
	Pasture area (ha)	30 ± 19	31 ± 18
	Milk production (L/cow/day)	6 ± 1.76	7 ± 2.02
Milk chemical composition	Fat	3.22 ± 0.63	3.57 ± 0.54
	Protein	2.99 ± 0.10	3.07 ± 0.10

CPS Conventional pastoral systems, *SPS* Silvopastoral systems

Results

Biotechnical characteristics

From the information on the farm characteristics (Table 1), the Animal Units per hectare (AU/ha) were obtained, showing a higher value in CPS than in SPS (0.5 versus 0.3 AU/ha).

Greenhouse gas emissions

There was lower emission intensities in SPS compared to CPS, as shown in Fig. 2, with N_2O at 0.28 versus 0.54 kg CO_2-eq/kg FPCM and CH_4 at 3.63 versus 7.29 kg CO_2-eq/kg FPCM. However, emissions per unit area showed no significant differences ($P > 0.05$).

Carbon storage

The average carbon storage in SPS was significantly higher than in CPS, with 3.48 t CO_2-eq/ha/year compared to 0.31 t CO_2-eq/ha/year, as shown in Fig. 3.

Water footprint

Silvopastoral systems exhibited lower water consumption per kg of protein produced (24 m^3) compared to CPS (39 m^3), as shown in Fig. 4 ($P < 0.05$).

Economic analysis

The SPS system generated higher economic returns, with an average annual income of $40,422

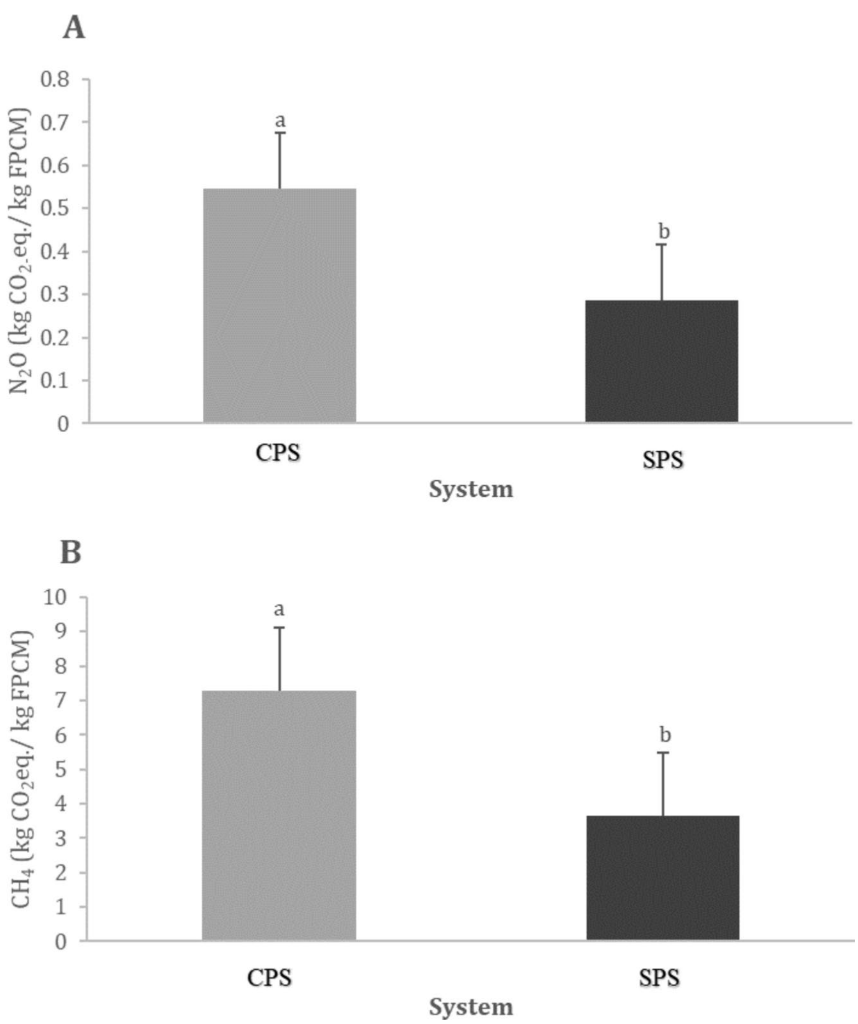

Fig. 2 Emission intensity of greenhouse gases in conventional pastoral (CPS) and silvopastoral systems (SPS) in the Peruvian Amazon. **A** Nitrous oxide emission (N_2O). **B** Methane emission (CH_4). N_2O (p = 0.028), CH_4 ($p = 0.035$)

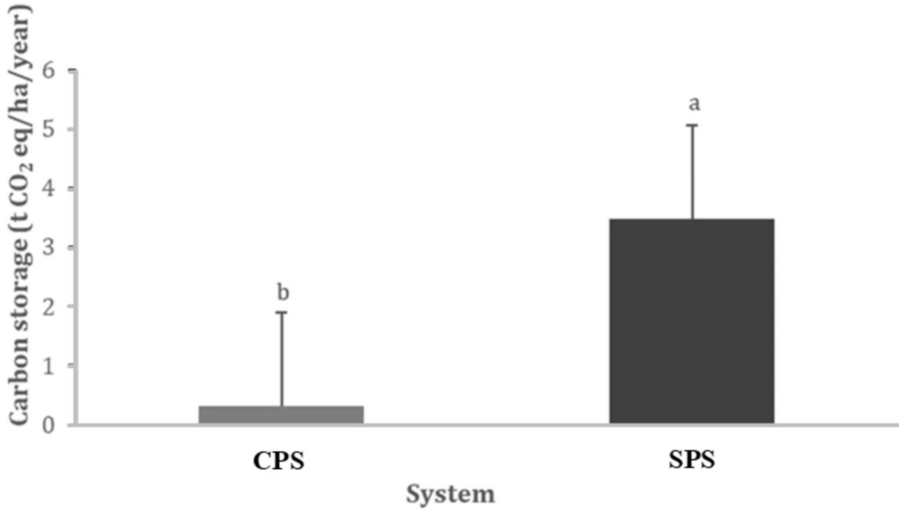

Fig. 3 Carbon storage in conventional pastoral (CPS) and silvopastoral systems (SPS) in the Peruvian Amazon. $p = 0.040$

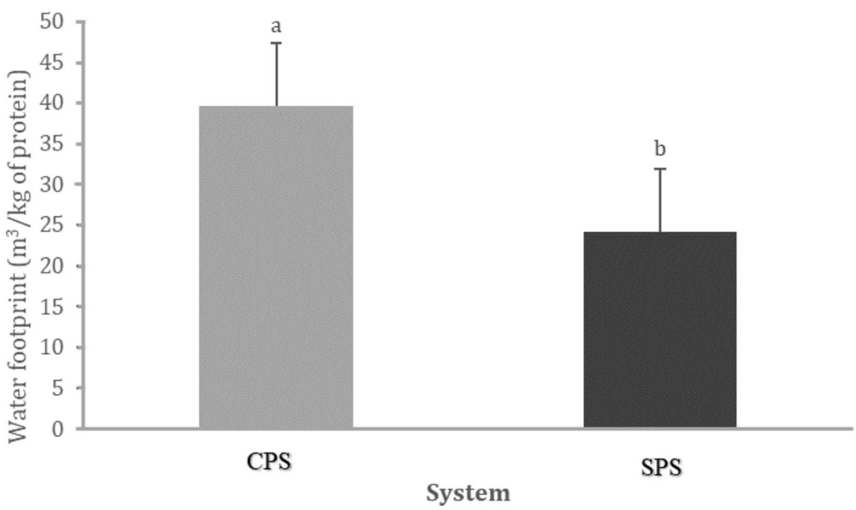

Fig. 4 Water footprint in protein production within conventional pastoral (CPS) and silvopastoral systems (SPS) in the Peruvian Amazon. $p = 0.047$

Table 2 Economic analysis of conventional pastoral (CPS) and silvopastoral systems (SPS) in the Peruvian Amazon

Item	CPS	SPS
Total investment ($)	333,133 a	283,693 a
Annual income ($)	22,830 a	40,422 a
Annual expenses ($)	19,860 a	34,503 a
Gross profit per year ($)	2970 b	5918 a
Gross profit per month ($)	248 b	493 a
Annual profitability (%)	27 b	35 a

Different letters in the row indicate a statistical difference at a 5% probability level

compared to $22,830 in the CPS. The annual gross profit was also greater in SPS ($5,918) than in CPS ($2,970), as shown in Table 2.

Discussion

The hypothesis that the use of a modeling tool would allow assessing the advantages of SPS in productive, socioeconomic, and environmental sustainability compared to current livestock systems in the high tropics of the San Martin region was accepted and the findings of this study support it. The analysis demonstrated that SPS outperformed CPS in several key areas, including GHG emissions, water use efficiency, and profitability.

Despite the advantages of SPS, the carrying capacity of *Brachiaria brizantha* cv. Marandú grass is estimated to be between 1.5 and 2.4 AU/ha (Lopes et al. 2013). According to our findings, both systems may be underutilized, or that the pastures have not reached their full production potential. Effective management practices, including soil correction, fertilization, biomass evaluation, stocking rate optimization, and soil quality improvement, are crucial for maximizing productivity. Overgrazing can lead to inadequate ground cover, increasing soil runoff and erosion risks (Bell et al. 2011), and contributing to higher greenhouse gas emissions (Nunes et al. 2019). Therefore, proper pasture management could enable more animals to be supported, further increasing productivity per unit area.

Additionally, studies indicate that estimates using the Tier 1 methodology introduce uncertainty into emission factors for livestock production, as they rely on predetermined values rather than calculated data (Parra and Mora-Delgado 2019). Nevertheless, these methods are commonly used due to their low cost and practicality, allowing for emissions estimates without direct measurements of CH_4 or N_2O. According to Silva-Parra et al. (2021), the mitigation potential of SPS as a management strategy can vary significantly based on site-specific conditions. This study demonstrates that SPS generally enhances productivity while reducing emissions per unit of meat, milk, or protein produced (emission intensity). These findings are consistent with studies by Rivera-Ferre et al. (2016), who found significant reductions in GHG emissions in SPS. The integration of trees into livestock systems contributes to greater resource use efficiency and, therefore, to a lower carbon footprint per product unit.

Our results showed that compared to CPS, SPS achieved a 50% reduction in total CO_2-eq/kg FPCM emissions. This reduction is notably higher than the 12% decrease reported by Rivera et al. (2016) in SPS with *Leucaena leucocephala*, which emphasized the effectiveness of SPS in minimizing emissions than an intensive system based on star grass (*Cynodon plectostachyus* (K.Schum.) Pilg.), irrigation, concentrated feed supply, and fertilization under tropical conditions (2.05 versus 2.34 kg of CO_2-eq, respectively). This study's findings align with the results of Salazar et al. (2024), who demonstrated that SPS in the Peruvian Amazon have a significantly greater capacity to capture and store carbon compared to CPS. The improvement in carbon sequestration contributes to climate change mitigation objectives and enhances overall soil health and biodiversity in these systems.

On the other hand, one reason for the higher carbon sequestration in SPS is the presence of trees, which can capture and store significant amounts of carbon dioxide during photosynthesis. Aryal et al. (2019) highlighted that SPS can also sequester carbon in the soil through the decomposition of leaf litter, contributing between 1.1 and 2.1 tons of carbon per hectare (4.07–7.7 t CO_2-eq/ha/year).

Furthermore, CLEANED estimated the water expenditure for animal production based on the total water requirement for food production, specifically the total evapotranspiration as a proportion of total precipitation (Notenbaert et al. 2016). In this study, SPS consumed 38.4% less water compared to CPS, which aligns with findings from Chará and Murgueitio (2005) that emphasize the role of trees in restoring forest functions in grazing areas. Trees help protect soil structure and increase water retention capacity through their diverse root systems (Morales-Ruiz et al. 2021).

Regarding water consumption, it was found that SPS require 24 m^3/kg of protein produced, compared to 39 m^3/kg for CPS ($P<0.05$). This more efficient use of water in SPS is supported by previous research that demonstrated that the presence of trees in livestock systems improves soil water retention and reduces runoff (Ibrahim et al. 2010). The improvement in water efficiency is crucial in the context of climate change and increasing water scarcity.

The advantages of SPS also extend to economic benefits, as they provide a favorable ratio of animals in production to liters of milk produced (7 L/cow/day; Table 1) along with additional income from wood and firewood sales. Previous studies indicated that implementing SPS can increase the value of traditional land use by 3–30%, primarily due to the demand for wood-derived products (Husak and Grado 2002). Our study corroborates those findings, demonstrating an annual profitability of 35% in SPS, higher than CPS.

However, it is crucial to note that the average price for milk sales in the study area was $0.41, with no significant differentiation between the systems. Milk in the country is primarily traded based on quantity rather than quality, meaning that SPS farmers do not receive additional compensation for their environmentally friendly practices. This economic challenge for wider adoption of SPS is consistent with the findings of Cubbage et al. (2012), who pointed out the need for specific economic incentives to encourage the adoption of silvopastoral practices. The implementation of policies that recognize and reward the ecosystem services provided by SPS could increase their economic viability and encourage wider adoption.

Conclusion

The evaluation of tropical dairy systems using the CLEANED tool identified SPS as the most sustainable option, demonstrating greater efficiency in water use—both in terms of incoming resources (precipitation, available water) and outgoing resources (milk, meat, and protein production). Additionally, SPS were economically feasible, yielding higher profits per animal per year and lower greenhouse gas emissions compared to CPS. However, the study's scope was limited, and results may vary based on local conditions, management practices, and livestock types. In addition, the CLEANED tool is limited to providing accurate estimates of economic impact; however, it can be complemented with a cash flow economic analysis.

While SPS showed promise in improving environmental sustainability, the lack of clear economic incentives for adoption could hinder its widespread implementation. Our findings suggested that appropriate policies and support mechanisms are necessary to facilitate the transition towards more responsible and environmentally friendly production practices in the dairy sector.

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Author contributions V.I. Conceptualization, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing—original draft, and Writing—review & editing. D.P. Investigation, Methodology, Visualization, Writing—original draft, and Writing—review & editing, E.F. Conceptualization, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing—original draft, and Writing—review & editing. C.G. Data curation, Software, Validation, Visualization, Writing—original draft, and Writing—review & editing. M.W. Resources, Software, Supervision, Validation, Visualization, Writing—original draft, and Writing—review & editing. V.P. Writing—original draft, and Writing—review & editing, J.A. Writing—original draft, and Writing—review & editing., G.R. Writing—original draft, and Writing—review & editing. C.G. Conceptualization, Investigation, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing—original draft, and Writing—review & editing.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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