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Determinants of Sustainable Cattle Farming to Guide Policy and Intervention in Perú

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ABSTRACT

The absence of detailed knowledge about the factors that determine the sustainability of cattle farming has led, in many cases, to the formulation of policies and interventions that lack contextual relevance and sensitivity to the structural heterogeneity of livestock farms. The objective of this study was to identify the important factors that determine the sustainability of cattle farming systems through a three-dimensional analytical framework based on 16 key indicators. Based on these factors, this study recommends strategic interventions to improve the environmental stewardship, resilience, productivity, and overall household welfare of cattle farming. Using probability sampling, data were collected from 120 farmers and analyzed using cluster analysis, principal component analysis (PCA), ANOVA, and Spearman correlation. The results revealed five distinct groups of cattle farmers differentiated by the age of the producer, economic dependence on cattle farming, annual yield, land use specialization, water availability, and soil erosion. Of these groups, Group 2 is particularly notable, with the highest sustainability index (64.03%), higher economic income, and greater economic dependence on cattle farming. While older producers with larger farms had higher economic and environmental scores, they also faced challenges such as a greater risk of erosion. By contrast, younger producers had less active but more innovation potential. Agricultural training was moderately related to better water management. These discoveries emphasize the need to formulate public policy and intervention strategies that focus on improving rural areas, diversification, enhancing education and improving ecological practice, while recognizing the heterogeneity of production profiles.

Keywords: *agricultural training; economic dependency; public policies; silvopastoral systems; water resource management*

INTRODUCTION

Sustainability is known as a multidimensional and systemic concept that integrates social, economic, and environmental dimensions within a unified framework (Bacon *et al.*, 2012; Ben-Eli, 2018; Stock & Burton, 2011). This integration, often referred to as the triple bottom line approach (Cirella & Russo, 2020), provides a basis for evaluating production systems, leading to decisions regarding resource management (Bacon *et al.*, 2012; Ouali *et al.*, 2023). However, most government interventions are standardized for all farmers without taking into account the heterogeneity between farms or the factors that determine this variability (Benitez-Altuna *et al.*, 2023). This situation has limited the application of strategies adapted to the socioeconomic and environmental conditions of production units with similar characteristics.

At the same time, the adoption of emerging technologies, such us remote sensing, digital monitoring, and artificial intelligence, has shown promising results in improving production, optimizing resource use, and environmental management (Biswas *et al.*, 2023). Nevertheless, the advancement of sustainable livestock systems requires not only technical innovation but also the strengthening of social structures and institutional support. The development of value chains, capacity-building initiatives, and multisectoral policies is pivotal for the long-term viability of livestock production (Bousbia *et al.*, 2024; Sandoval Yate *et al.*, 2024). On the other hand, policies must promote household integration, gender equality, education, agricultural training, and access to basic services, which are essential for strengthening the human dimension of sustainability. The participation of women has been shown to promote diversification and adaptability (Mulema *et al*., 2019), and household efficiency and cohesion have been strengthened by decision-making involving all household members (Gómez Urrutia & Jiménez Figueroa, 2015; Porto & Sili, 2020). Likewise, improved access to water, electricity, and sanitation directly affects productivity and quality of life. Higher education levels are also correlated with greater adoption of innovative and sustainable practices (Zarei *et al*., 2020). The implementation of sustainable practices such as silvopastoral systems (SPSs) represents an alternative that integrates pastures, trees, and cattle farming on the same plot of land. These systems provide numerous benefits, such as optimizing soil structure, increasing organic matter, reducing erosion, and increasing biodiversity (Huertas *et al*., 2021; Murgueitio *et al*., 2013). From a production perspective, SPSs contribute to animal welfare by providing shade and shelter from heat and heavy rains while increasing livestock productivity (Fernández *et al*., 2024), making them a strategic component of sustainable livestock development.

In this context, cattle farming is a strategic sector for sustainable development, where livestock systems contribute significantly to household income, food security, and landscape management (FAO, 2025; Varijakshapanicker *et al*., 2019). To date, however, no studies have been conducted to identify the factors that influence the sustainability of this activity in the provinces of Jaén and San Ignacio in northern Peru, even though numerous families in this area depend on livestock as their only source of livelihood. There is little knowledge about the most significant variables that should be prioritized and strengthened by state policies and interventions to improve producers' income and quality of life. Therefore, the objective of this research is to identify the most relevant variables that determine the sustainability of livestock production systems using a three-dimensional analytical framework that encompasses social, economic and environmental indicators and is based on the hypothesis that systems with higher specialization and economic returns and better access to rural services that have adopted environmentally friendly ecological practices have significantly higher levels of sustainability. Based on these factors, this study recommends strategic interventions to improve the environmental responsibility, resilience, productivity, and overall well-being of livestock-producing households.

METHODS

The present study was conducted in cattle-producing districts within the provinces of Jaén and San Ignacio, which are located in the Cajamarca region, northern Peru. Specifically, the districts of Chontalí, Huabal, and Jaén in the province of Jaén, as well as Chirinos, Huarango, San Ignacio, and San José de Lourdes in the province of San Ignacio, were included in the analysis. These areas are characterized by diverse topographic and ecological features and altitudes that range from 333 to 3,963 meters above sea level (Figure 1). The climate varies significantly, transitioning from cold highlands to humid tropical conditions in the lowlands, with temperatures ranging between 11 °C and 33 °C and annual precipitation levels reaching up to 1,000 mm (SENAMHI, 2025).

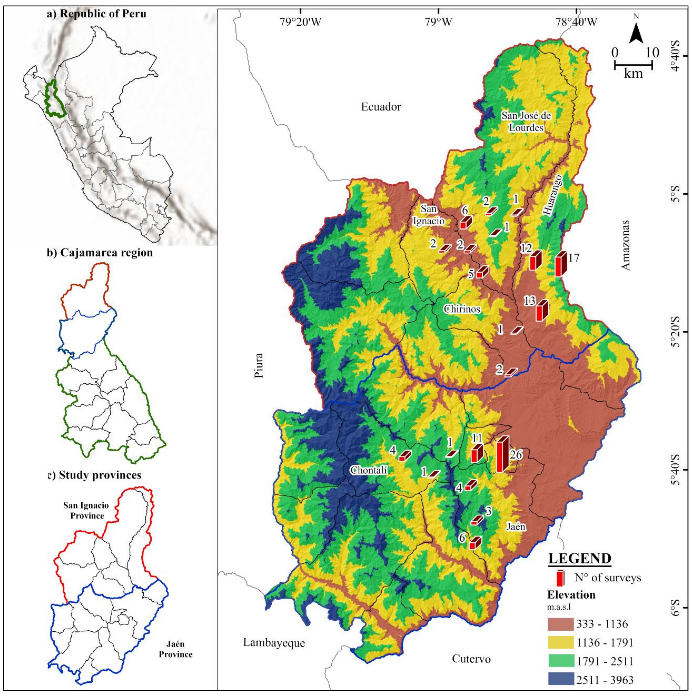

Figure 1. Location map of livestock systems in the provinces of Jaén and San Ignacio. The red boxes represent the number of producers interviewed in each specific area. This map was created by the authors using open-access resources. The provincial and district boundaries were obtained from the Geoportal of the National Geographic Institute of Peru (IGN) (https://www.idep.gob.pe/geovisor/VisorDeMapas-3D/) in shape file format with a DATUM WGS 1984. The map is for illustrative purposes only.

Study Population and Sampling

The study population consisted of 639 cattle producers officially registered with the Regional Management of Economic Development of the Provincial Municipality of Jaén and the Jaén-San Ignacio-Bagua Special Project (PEJSIB) made up the study population. Of these, 120 producers were selected using a simple random sampling, without stratification or the application of specific selection criteria. Although no measures were taken to select specific groups within the population, the sampling included all registered producers, allowing the selected sample to adequately reflect the characteristics of the population as a whole. Consequently, the representativeness of the sample stems from the comprehensiveness of the sampling frame and the unbiased nature of the random selection process. This approach minimizes selection bias and increases the validity and generalizability of the study findings (Lohr, 2021). Prior to data collection, all participants provided oral informed consent. The surveys were conducted in person by trained interviewers to ensure the consistency and accuracy of the responses. The methodological flow for identifying the determining factors of sustainability in cattle farming and estimating the sustainability index is shown in Figure 2.

Data Collection and Indicators

Fieldwork was conducted between February and May 2024. A structured survey was used to collect data on 16 key indicators distributed across three dimensions of sustainability: social (7 indicators), economic (3 indicators), and environmental (6 indicators) (Barrezueta-Unda, 2018; Torres Jara de García *et al.*, 2023). The indicators for categorical variables were assigned scores from 0 to 10 according to the Likert scale, with higher values representing more favorable conditions. The evaluation criteria and guidelines are detailed in Table 1. Within the economic dimension, one of the core indicators was the degree of economic dependence on cattle farming (DECONAG), which was measured as the proportion of household income derived from cattle-related activities. Unlike other indicators that focus solely on cattle farming income, such as annual yield (RENA), this variable captures the relative contribution of milk and meat sales to the household economy as a whole. Scores for DECONAG were assigned based on producers' verbal responses: households in which livestock accounted for 50% or more of total income were assigned 6 points, whereas those with lower levels of dependency received 4 points. This indicator reflects the extent of financial reliance on cattle farming regardless of the presence of other income sources. The concept of income in this study was specific to cattle-based production; therefore, annual yield (RENA) was calculated by aggregating revenues from meat and milk sales. Meat income was estimated based on reported animal sales by producers, average live weight (kg), and a standardized meat price of S/6.2 per kg (INEI, 2023). Milk income was computed assuming 305 lactation days per year per cow (Williams *et al.*, 2021) with an average yield of 6.2 liters/day (Gobierno

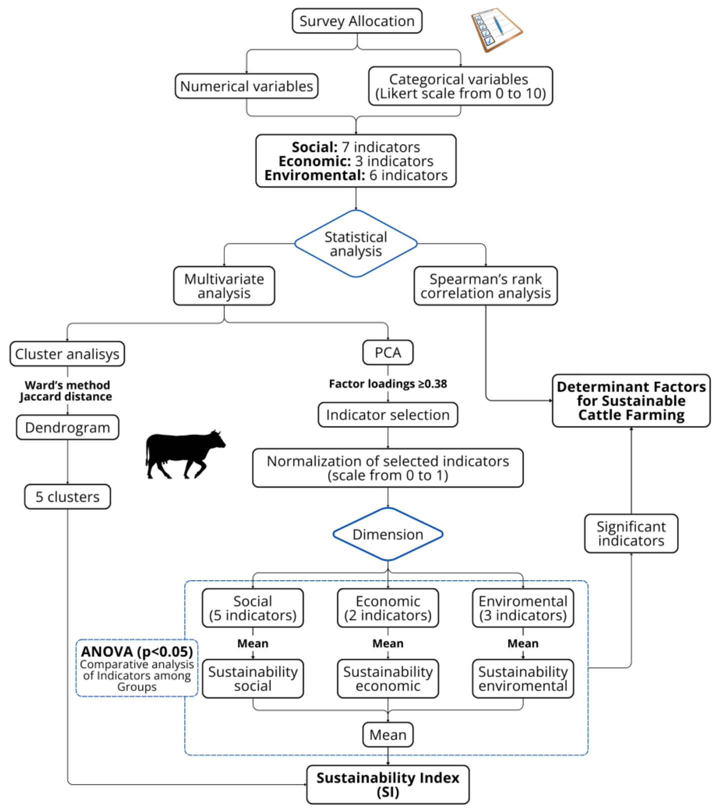

Figure 2. Methodological flow for identifying the determinants of cattle farming sustainability and estimating the sustainability index.

Table 1. Indicators for social, economic, and environmental dimensions according to the premise and weights of importance (scores) established to determine the sustainability of cattle farming systems in Jaén and San Ignacio

Dimension	Indicator	Premise	Score	Fountain
Social	Producer age (AGE)	Producer age	Numerical variable	Proposed by the author
	Rural life (Distance in km) (VIR)	The farma is located 0 to 2 km from the nearest town with amenities	8	Proposed by the author based on the premise presented by Barrezueta-Unda (2018)
		The farm is located 2 to 4 km from the nearest town with services	6	
		The farm is located 4 to 6 km from the nearest town with services	4	
		The property is >6 km from the nearest town with amenities	2	
	Basic services (SERB)	The farm has 3 basic amenities	4	Proposed by the author based on the premise presented by Barrezueta-Unda (2018)
		The farm has 2 basic amenities	3	
		The farm has a basic service	2	
	Equity (EQUI)	Participation of women in farm work ≥50%	8	(Barrezueta-Unda, 2018)
		Participation of women in farm work <50%	4	
		Nonparticipation of women in farm activities	2	
	Family integration in production and decision-making (IFPROD)	Decisions are made through mutual agreement among all family members	8	(Barrezueta-Unda, 2018)
		Participation is permitted exclusively for the parent or head of household	6	
		Decisions are made only by the parent or head of the household out of habit or necessity	4	
		Decisions are made after external advice or market requirements	2	
	Agricultural training (CAPAGRI)	Always (participated in more than 3 trainings in the last year)	8	Proposed by the author based on the premise presented by Barrezueta-Unda (2018)
		Sometimes (participated in at least 2 trainings in the last year)	4	
		Never (did not participate in training)	2	
	Agrarian affiliation (associativity) (FILA)	Has an agricultural affiliation	2	(Barrezueta-Unda, 2018)
		Has no agrarian affiliation	1	
Economic	Economic dependence on cattle farming (DECONAG)	Households where income from cattle farming represents ≥50% of total household income	6	Proposed by the author
		Households where income from cattle farming represents <50% of total household income	4	
	Annual yield (RENA) (Total income/year/farm)	Cattle income is greater than the average of all surveyed producers	8	Proposed by the author based on the premise presented by Barrezueta-Unda (2018)
		Cattle income between the annual minimum wage (S/ 12,300.00) and the sample average	4	
		Cattle income equal to or below the annual minimum wage (S/12,300.00)	2	
	Benefit/cost ratio (B/A)	Total revenue/cost of production	0-10	
Environmental	Availability and use of organic inputs (DUAO)	The farm had access to both inorganic and organic inputs, such as plant debris and livestock manure, for pasture management.	2	Proposed by the author based on the premise presented by Barrezueta-Unda (2018)
		The farm did not have access to inorganic and organic inputs, such as plant residues and livestock manure, for pasture management.	1	
	Silvopastoral systems (SPS)	At least 50% of your land has SPS	8	Proposed by the author based on the premise presented by Barrezueta-Unda (2018)
		Less than 50% of your land has SPS	6	
		Does not have SPS	4	
	Specialization of the farm (ESPEX)	The ESPEX value was obtained by dividing the area dedicated to pasture cultivation by the total farm area. The value obtained was multiplied by 10 to standardize the evaluation scale. The values range from 0 to 10; where values closer to 10 represent a higher degree of specialization.	0-10	Proposed by the author based on the premise presented by Barrezueta-Unda (2018)
	Water availability (AGFI)	Drinkers	10	Proposed by the author based on the premise presented by Torres Jara de García *et al*. (2023)
		Pipes and/or hoses	5	
		Water springs, streams, etc.	1	
	Soil erosion (EROS)	Low (no soil loss due to rainfall or other weather conditions)	10	Proposed by the author based on the premise presented by Torres Jara de García *et al*. (2023)
		Moderate (surface soil dragging during rainy periods or when irrigating)	5	
		High (landslides or loss of soil due to runoff during rainy periods)	1	
	Arable layer (CAPA)	Deep: optimal arable layer for root development	10	Proposed by the author based on the premise presented by (Torres Jara de García *et al*., 2023)
		Moderate: sufficient arable layer for crops	5	
		Minimal: shallow or rocky soil	1	

regional de Cajamarca, 2023) and a market price of S/1.4 per liter (INEI, 2023).

In the environmental dimension, the indicator availability and use of organic inputs (DUAO) was assessed as an indicator reflecting the extent to which livestock farms incorporate organic matter and other inputs into pasture management practices. A value of 2 was assigned when the farm had access to both inorganic and organic inputs, such as crop residues and livestock manure, and a value of 1 when the farm did not have access to these inputs.

Statistical Analysis

Using Ward's method and the Jaccard distance, a hierarchical cluster analysis was performed, grouping producers according to their production similarities (Torres Jara de García *et al.*, 2023). This analysis showed the formation of five clusters. Nonparametric Kruskal–Wallis tests were used to compare numerical variables across clusters. Next, all variables were standardized (mean= 0, standard deviation= 1) to ensure comparability of the scale (Ruiz-Méndez *et al.*, 2020). Principal component analysis (PCA) was then applied using the FactoMineR package in RStudio (Lê *et al.*, 2008) to identify the most influential variables contributing to the differentiation of the groups. For further analysis, variables with factor loadings ≥ 0.38 within the first five principal components (PCs) were selected. The selected indicators were normalized to a scale of 0 to 1 using Max–Min linear normalization (Equations (1) and (2)) adjusted on the basis of the expected sustainability outcome (Barrezueta-Unda, 2018; Pollesch & Dale, 2016). To detect statistically significant differences among groups for each normalized indicator, analysis of variance (ANOVA) was performed, followed by Tukey's post hoc tests ($p<0.05$). Finally, to identify interdependencies between indicators and detect possible redundancies, a Spearman's rank correlation analysis was performed using the Psych package of RStudio software. To increase the interpretability of the correlations, green rectangles were drawn within the correlation matrix to highlight the most relevant relationships between variables. Asterisks indicate levels of statistical significance: $p<0.05$ (*), $p<0.01$ (**), and $p<0.001$ (***). This analysis complemented the PCA by revealing statistically significant associations between key variables linked to sustainability.

Equation 1: Max-Min normalization (positive indicators):

$$Vn = \frac{V - V_{min}}{V_{max} - V_{min}}$$

Equation 2: Inverted normalization (negative indicators):

$$Vn = 1 - \frac{V - V_{min}}{V_{max} - V_{min}}$$

where: Vn is the normalized value, V is the observed value not normalized, Vmin is the Minimum value observed, and Vmax is the Maximum value observed.

Sustainability Index Calculation

To determine the sustainability index (SI), each normalized indicator (range from 0 to 1) was summed within its respective dimensions, and an average score was obtained for the social, economic, and environmental dimensions. The overall SI was then calculated as the arithmetic mean of the scores obtained in these three dimensions multiplied by 100 to obtain a percentage value (Equation 3) (Barrezueta Unda, 2018; Escribano *et al*., 2014). To facilitate interpretation, the SI was classified into three categories according to predefined percentage thresholds: low sustainability (<30%), medium sustainability (≥30 and <60%), and high sustainability (≥60%).

Equation 3: Sustainability Index (SI):

$$SI = \frac{S_{social} + S_{economic} + S_{environmental}}{3} \times 100$$

where: SI is sustainability index (percentage value), S_{social} is sustainability social, $S_{economic}$ is sustainability economic, and $S_{enviromental}$ is sustainability environmental.

RESULTS

The cluster analysis using Ward's method identified five distinct groups of livestock producers on the basis of similarities in their socioproductive characteristics (Figure 3). These clusters reflect both geographic and productive variability among farms in the provinces of Jaén and San Ignacio. Group 1 comprised the youngest producers (43 years) who managed the smallest herds (3 cows) and owned the smallest pasture area (2 ha). In contrast, Group 3 included the oldest producers (58 years), with the largest number of cattle on their farms, which is in the interquartile range of 8 to 32 cattle, this being the highest value among all groups; with large tracts of land (12 ha), and approximately 10 ha of pasture. Intermediate characteristics were observed in Groups 2, 4, and 5 (Table 2). These differences underscore the diversity of livestock systems in the study area and suggest that producers' age, cattle herds, and land access play central roles in shaping production strategies.

These clusters reflect both geographic and productive variability among farms in the provinces of Jaén and San Ignacio. Group 1 comprised the youngest producers (average age: 41.4 ± 10.6 years) who managed the smallest herds (6.5 ± 4.1 cattle) and owned the least amount of total land (6.8 ± 5.5 ha) and pasture area (3.3 ± 3.5 ha). In contrast, Group 3 included the oldest producers (58.5 ± 16.2 years) with the largest herds (25.9 ± 29.1 cattle) and extensive landholdings (23.7 ± 26.7 ha), with an average of 0.6 ha of pasture. Intermediate characteristics were observed in Groups 2, 4, and 5 (Table 2). These differences underscore the diversity of livestock systems in the study area and suggest that producers' age, cattle herds, and land access play central roles in shaping production strategies.

PCA revealed the formation of 14 PCs; of these, the top 10 were selected and accounted for more than

85.48% of the accumulated variance (Figure 4). Five social variables, two economic variables, and three environmental variables were extracted based on their factor loadings (≥ 0.38) in the first five PCs (Table 3). The PCA in PC 1 revealed that the most influential variables were the economic variable DECONAG (economic dependence on cattle farming) and the social variable AGE (age of the producer), suggesting that these variables were significant for the first principal component. For PC 2, the social variable ESPEX (specialization of the farm) was the most prominent (Figure 5). This suggests that farms with larger pasture areas relative to the total area contribute significantly to the variation observed in the second principal component.

Analysis of the normalized indicators across groups (Table 4; Figure 6) revealed distinct patterns in the sustainability dimensions. Social dimension: While there were no significant differences in most social indicators (age, access to services, gender equity, training), AGE emerged as an exception and showed significant variation among Groups 2, 4, and 5 ($p<0.05$). This finding suggests a generational divide in producers' profiles, with older farmers predominating in Group 3 and younger farmers constituting Group 1. Conversely, Groups 2 and 5 exhibited intermediate age ranges with

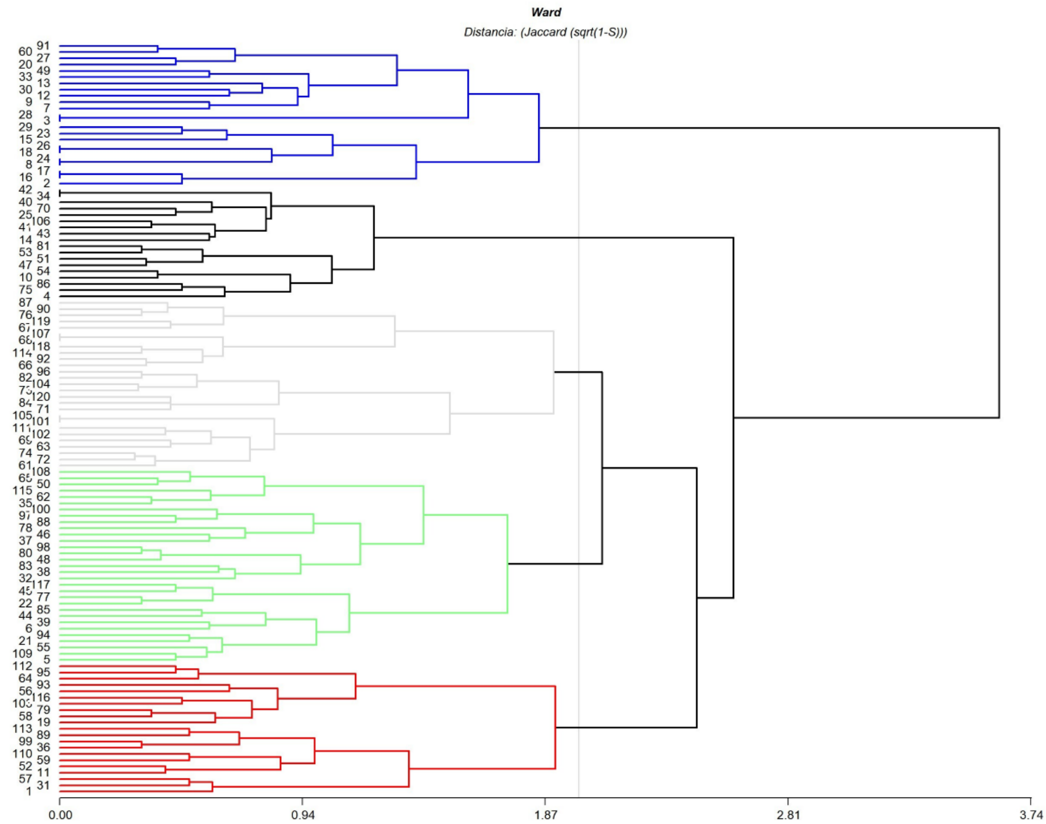

Figure 3. Dendrogram representing the hierarchical clustering of livestock systems using Ward's method with Jaccard distance (cophenetic correlation coefficient = 0.462). Five distinct clusters were identified and color-coded as follows: Group 1 (blue): 23 producers; Group 2 (black): 18 producers; Group 3 (lead gray): 27 producers ; Group 4 (green): 31 producers; and Group 5 (red): 21 producers. The grouping reveals heterogeneity in production systems based on social, economic, and environmental characteristics.

Table 2. Means of the nonparametric Kruskal–Wallis test of the quantitative variables according to the groups

Indicator	Group 1 (n=23) Mean ± SD	Group 2 (n=18) Mean ± SD	Group 3 (n=27) Mean ± SD	Group 4 (n=31) Mean ± SD	Group 5 (n=21) Mean ± SD	H	p value
AGE	41.39 ± 10.57 [a]	53.22 ± 12.16 [bc]	58.52 ± 16.22 [c]	50.00 ± 12.08 [b]	49.90 ± 13.58 [bc]	20.11	0.001
Total cattle	6.48 ± 4.05 [a]	23.22 ± 21.96 [b]	25.89 ± 29.05 [b]	21.13 ± 26.68 [b]	12.19 ± 17.32 [a]	27.92	<0.0001
Cows	3.70 ± 2.36 [a]	12.28 ± 15.57 [b]	13.93 ± 16.5 [b]	11.35 ± 16.02 [b]	7.48 ± 13.49 [a]	23.53	0.000
Total property	6.78 ± 5.47 [a]	20.22 ± 33.55 [abc]	23.74 ± 26.66 [c]	18.06 ± 25.32 [bc]	16.76 ± 42.78 [ab]	13.32	0.010
Pasture area	3.28 ± 3.52 [a]	13.17 ± 21.33 [bc]	20.63 ± 24.31 [c]	13.19 ± 16.26 [bc]	8.31 ± 10.92 [b]	27.65	<0.0001

Note: H represents the Kruskal–Wallis test statistic used to compare groups without assuming normality. Means with different letters are significantly different ($p<0.05$). The numbers in parentheses represent the number of producers in the group.
AGE is the age of the cattle producer.
Total cattle include all bovine categories present on the farm, such as adult bulls, cows, heifers, young females, and calves (male and female). This aggregate figure captures the full herd structure managed by the producer at the time of the survey. The total property area refers to the entire landholding managed by the producer, including both pastureland and other land uses (e.g., cropland or land with no defined use). In contrast, the pasture area refers specifically to the part of the land dedicated exclusively to cattle grazing.

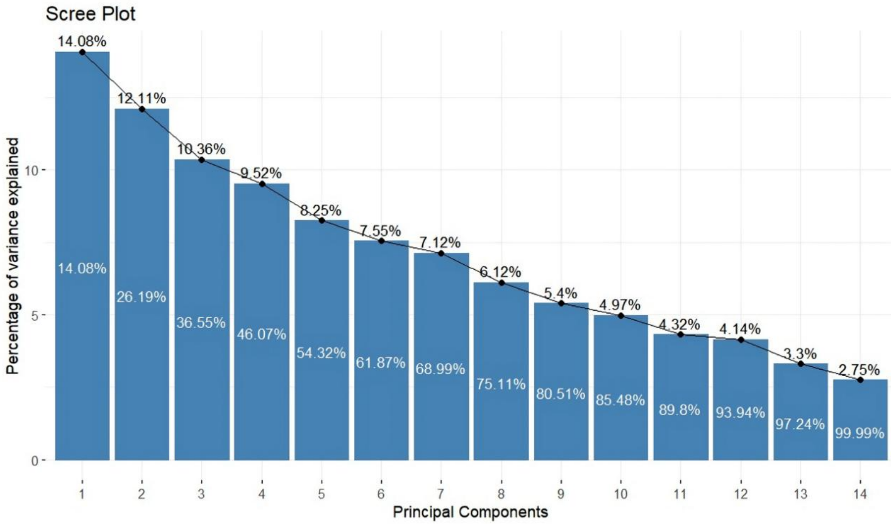

Figure 4. Scree plot derived from principal component analysis (PCA), displaying the individual contribution of each component to total variance (bars) and the cumulative variance explained (line). The first 10 components account for more than 85% of the total variance, justifying their selection for further analysis.

Table 3. Variables selected on the basis of their factor loadings (≥ 0.38) in the first principal component (PC) identified by PCA

Variables	Principal components (PC)													
	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12	PC13	PC14
AGE	-0.38741	0.193682	0.28057	0.00565	-0.16404	-0.05087	-0.36756	-0.01018	0.20597	-0.47501	-0.4703	-0.05444	0.21151	0.17894
VIR	-0.00353	0.06123	-0.11384	0.09082	0.231769	0.784753	0.09369	0.47896	0.12781	-0.19572	-0.03023	0.08407	0.05941	-0.0338
SERB	-0.16264	-0.24871	-0.28637	-0.2383	0.483212	0.190802	-0.0815	-0.48077	-0.2154	0.062964	-0.17749	0.07998	0.29786	0.297
EQUI	-0.22329	0.304668	0.19344	-0.2055	0.397249	-0.03845	-0.4855	0.01388	-0.084	-0.03813	0.45928	0.266728	-0.23105	-0.19634
IFPROD	-0.04677	0.35649	0.29976	-0.02	-0.11265	0.40972	0.1849	-0.53282	0.32222	0.238173	0.12921	-0.21693	-0.182	0.15629
CAPAGRI	-0.05165	0.3656	-0.19031	0.16215	0.392854	-0.32508	0.41869	0.00307	0.2705	-0.06179	-0.27793	0.351648	-0.2666	0.12989
FILA	0.047851	0.070272	-0.2791	-0.5868	-0.12664	-0.08842	0.27382	-0.07764	0.26295	-0.49763	0.32229	-0.0828	0.16804	-0.09994
DECONAG	-0.45839	-0.33353	0.16579	-0.0961	-0.05715	-0.07166	0.2077	0.29578	0.03334	0.050531	0.30483	0.01697	-0.18947	0.60838
RENA	-0.191	-0.18319	0.46042	-0.23274	0.390772	-0.11648	0.29771	0.14498	0.14107	0.19577	-0.17605	-0.28353	0.20556	-0.4195
SPS	-0.30383	0.27084	-0.0149	-0.29128	-0.24505	0.135539	0.29004	0.02271	-0.6626	-0.01567	-0.25204	0.03382	-0.24296	-0.1524
ESPEX	-0.35562	-0.38554	0.02012	0.21343	-0.24199	0.120394	0.12481	-0.2914	0.17329	-0.07675	0.06026	0.544943	-0.00576	-0.4109
AGFI	-0.30316	0.328168	-0.0773	0.46993	0.040614	-0.10082	0.20993	-0.0208	-0.2233	-0.03031	0.37032	-0.14683	0.55453	-0.0169
EROS	-0.37811	-0.12701	-0.4623	0.19339	0.09726	-0.01429	-0.14658	-0.0542	0.1233	-0.06516	-0.01647	-0.56171	-0.4144	-0.2207
CAPA	-0.25727	0.218498	-0.3538	-0.2641	-0.24356	-0.0196	-0.17976	0.22789	0.29402	0.6085	-0.09581	0.13783	0.24636	-0.0397

Note: The abbreviations used in this study are as follows: principal component (PC), principal component 1 (PC1), principal component 2 (PC2), principal component 3 (PC3), up to principal component 14 (PC14).
The variables included in the table are defined as follows: producer age (AGE), rural life (Distance in km) (VIR), basic services (SERB), equity (EQUI), family integration in production and decision-making (IFPROD), agricultural training (CAPAGRI), agrarian affiliation (FILA), economic dependence on cattle farming (DECONAG), annual yield (RENA), silvopastoral systems (SPS), specialization of the farm (ESPEX), water availability (AGFI), soil erosion (EROS) and arable layer (CAPA).

no significant divergence between them, indicating a more heterogeneous or transitional demographic structure (Table 2). Despite these internal differences, overall social sustainability performance remained relatively balanced across the groups, with mean scores ranging from 0.52 to 0.56 (Table 4).

Economic dimension: Statistically significant differences were observed between the groups in terms of economic indicators, economic dependence on cattle farming (DECONAG), and annual yield (RENA). Group 2 had the highest economic dependence, with a score of 1.00, and the highest RENA value (0.65), reflecting higher productivity in terms of milk and meat sales (Table 4). The results suggest a high degree of specialization and economic dependence on livestock, which may be related to more intensive management practices and greater market orientation. In contrast, Group 5 had the lowest DECONAG value (0.33) and a RENA value of 0.42, suggesting limited income generation. Group 3, despite having the largest herds and farms (Table 2), obtained the lowest RENA score (0.23) but a DECONAG of 0.74 (Table 4). This suggests that size alone does not guarantee higher income, possibly because of lower productivity per animal or market access limitations. On the other hand, Groups 1 and 4 presented moderate values for both indicators, reflecting a transitional profile with growth potential.

Environmental dimension: Significant differences were observed between the groups in all the environmental indicators evaluated, particularly the

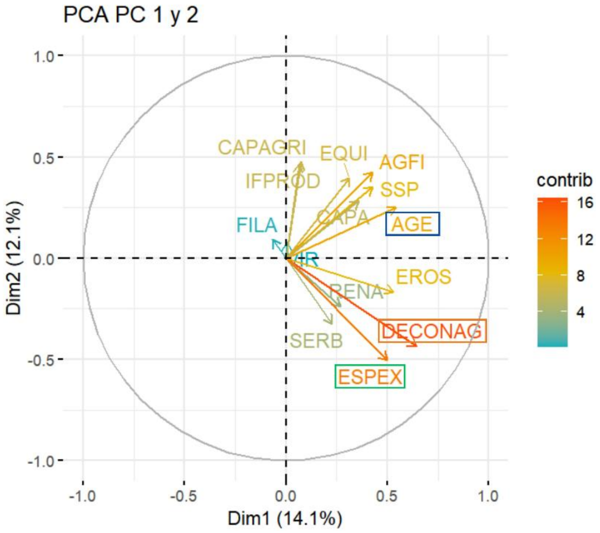

Figure 5. Biplot of the first two principal components (PC1 and PC2) from the principal component analysis (PCA), highlighting the contributions of social (blue), economic (orange), and environmental (green) indicators. The vector length and color intensity (from blue to red) indicate the relative weight of each variable in the formation of the components. Economic dependence on cattle farming (DECONAG) and producer age (AGE) are dominant in PC1, whereas specialization of the farm (ESPEX) is the primary contributor to PC2, aligning with the multidimensional structure of the data. The definitions of all the variables presented in the figure are detailed below: producer age (AGE), rural life (Distance in km) (VIR), basic services (SERB), equity (EQUI), family integration in production and decision-making (IFPROD), agricultural training (CAPAGRI), agrarian affiliation (associativity) (FILA), economic dependence on cattle farming (DECONAG), annual yield (RENA), silvopastoral systems (SPS), specialization of the farm (ESPEX), water availability (AGFI), soil erosion (EROS), arable layer (CAPA).

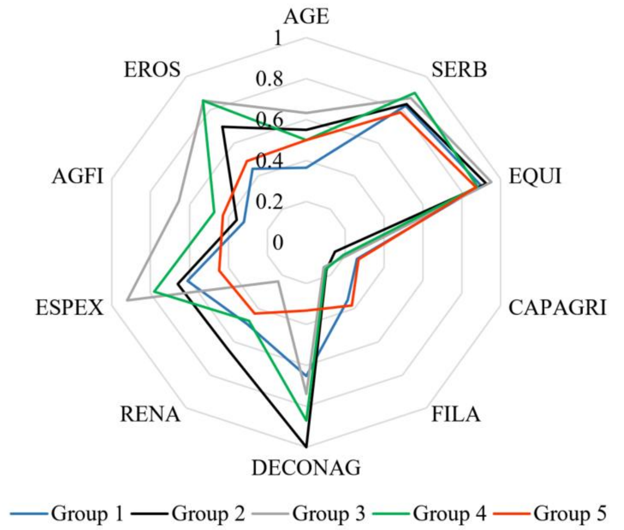

Figure 6. Radar plot illustrating the normalized mean values of key sustainability indicators across the five producer groups. Indicators are categorized by dimension: a) social: producer age (AGE), basic services (SERB), equity (EQUI), agricultural training (CAPAGRI) and agrarian affiliation (FILA); b) economic: economic dependence on cattle farming (DECONAG) and annual yield (RENA); and c) environmental: specialization of the farm (ESPEX), water availability (AGFI), and soil erosion (EROS). The plot highlights contrasting performance profiles, with Groups 2, 3, and 4 showing higher sustainability levels, particularly in economic and environmental dimensions. Conversely, within the social dimension, all groups exhibited minimal levels, particularly those pertaining to agricultural associativity and training.

specialization of the farm (ESPEX), water availability (AGFI), and soil erosion (EROS) indicators. In this regard, Group 3 presented the highest ESPEX value (0.92), indicating that almost all of its land area was used for livestock production. In addition, this group achieved higher values for both AGFI (0.65) and EROS (0.86), suggesting better access to water resources but agricultural practices that intensify soil erosion. Group 4 ranked closely behind with high specialization of the farm (ESPEX = 0.78) and a moderate level of water availability (AGFI = 0.47), reflecting a relatively specialized production system with acceptable access to water resources. In contrast, Group 5 had the lowest levels of specialization (ESPEX = 0.45) as well as intermediate values for AGFI and EROS, whereas Group 2 had intermediate scores for all the indicators evaluated. In contrast, Group 1, which was composed of younger producers (43 years) with smaller farms (2 ha of pasture) (Table 2), showed limited access to water (AGFI = 0.32) but the lowest levels of soil erosion (EROS = 0.44) (Table 4). These results highlight the need for differentiated interventions to strengthen ecological resilience and underscore the importance of promoting practices such as silvopastoral systems and adequate water management, especially on smaller and less specialized farms.

The composite SI revealed that Groups 1 and 5 were in the "low sustainability" category, with mean percentages of 52.3 and 46.6%, respectively. In contrast, Group 2 achieved the highest SI (64.0%), driven by strong economic performance and moderate scores in the social and environmental areas. Groups 3 and 4 also scored above 62%, with Group 3 standing out due to favorable environmental indicators but moderate economic scores (Table 4).

Spearman's correlation analysis (Figure 7), supported by principal component analysis (PCA) (Figure 5), revealed key interdependencies among the sustainability indicators. Economic dependence on cattle farming (DECONAG) was positively correlated with both farm specialization (ESPEX) (r = 0.35*) and annual yield (RENA) (r = 0.38***), indicating that more specialized farms with greater reliance on livestock activities tend to achieve greater productivity. Moreover, a moderate positive correlation between agricultural training (CAPAGRI) and water availability on the farm (AGFI) (r = 0.28**) suggests that increased technical training may improve resource management practices. Although a weak negative correlation was observed between producer age (AGE) and access to basic services (SERB) (r = –0.14), this correlation was not

Table 4. Analysis of variance of the normalized indicators and comparison of the sustainability index (percentage mean) for each group

Dimension	Normalized indicator	Group 1 (n=23)	Group 2 (n=18)	Group 3 (n=27)	Group 4 (n=31)	Group 5 (n=21)	DF model	p value
Social	AGE *	0.3655 [a]	0.5503 [b]	0.6331 [b]	0.500 [ab]	0.4985 [ab]	4	0.001
	SERB	0.8261 [a]	0.8333 [a]	0.8704 [a]	0.9032 [a]	0.7857 [a]	4	0.606
	EQUI	0.8986 [a]	0.9259 [a]	0.9506 [a]	0.8817 [a]	0.873 [a]	4	0.819
	CAPAGRI	0.2609 [a]	0.1481 [a]	0.2099 [a]	0.1935 [a]	0.2698 [a]	4	0.369
	FILA	0.3478 [a]	0.1667 [a]	0.1481 [a]	0.1613 [a]	0.381 [a]	4	0.156
	Mean	0.540	0.525	0.562	0.528	0.562		
Economic	DECONAG *	0.6522 [ab]	1.000 [bc]	0.7407 [c]	0.871 [bc]	0.3333 [a]	4	0.000
	RENA*	0.4928 [ab]	0.6481 [b]	0.2346 [a]	0.4731 [ab]	0.4286 [ab]	4	0.026
	Mean	0.573	0.824	0.488	0.672	0.381		
Environmental	ESPEX *	0.6106 [ab]	0.6598 [b]	0.9191 [c]	0.7803 [bc]	0.4463 [a]	4	<0.0001
	AGFI *	0.3188 [a]	0.358 [a]	0.6543 [b]	0.4731 [ab]	0.4286 [ab]	4	0.002
	EROS*	0.4444 [a]	0.6975 [ab]	0.856 [b]	0.8566 [b]	0.4921 [a]	4	<0.0001
	Mean	0.458	0.572	0.810	0.703	0.456		
Group 1	SI	52.34%						
Group 2	SI		64.03%					
Group 3	SI			62.00%				
Group 4	SI				63.45%			
Group 5	SI					46.61%		

Note: Variables with * are statistically significant. Means with different letters are significantly different (Tukey's p<0.05). Numbers in parentheses represent the number of producers in the group. All values are expressed on a standardized scale from 0 to 1, except for the SI, which is expressed as a percentage value. "Mean" represents the average score of the indicators within each sustainability dimension (social, economic, and environmental). The sustainability index (SI)" corresponds to the composite sustainability score, which is obtained by averaging the mean values of the three dimensions.

The definitions of all the variables presented in the table are detailed below: producer age (AGE), basic services (SERB), equity (EQUI), agricultural training (CAPAGRI), agrarian affiliation (FILA), economic dependence on cattle farming (DECONAG), annual yield (RENA), specialization of the farm (ESPEX), water availability (AGFI), soil erosion (EROS).

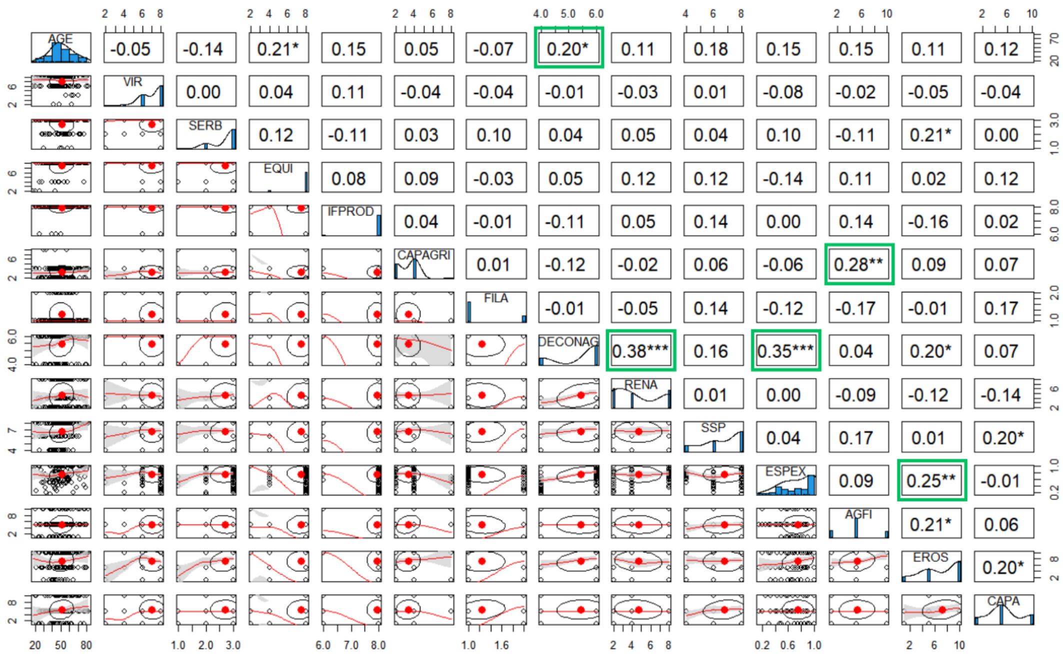

Figure 7. Spearman's rank correlation matrix among statistically significant relationships between sustainability indicators. Positive correlations are observed between economic dependence on cattle farming (DECONAG), specialization of the farm (ESPEX), and annual yield (RENA), showing that farms that are more specialized and dependent on livestock tend to report higher productivity. In addition, agricultural training (CAPAGRI) has a moderate association with water availability (AGFI), suggesting that greater technical knowledge is correlated with better resource management practices. The green rectangles represent the most important correlations between variables. Asterisks indicate levels of statistical significance: $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***). The definitions of all the variables presented in the figure are detailed below: producer age (AGE), rural life (Distance in km) (VIR), basic services (SERB), equity (EQUI), family integration in production and decision-making (IFPROD), agricultural training (CAPAGRI), agrarian affiliation (associativity) (FILA), economic dependence on cattle farming (DECONAG), annual yield (RENA), benefit/cost ratio (B/A), availability and use of organic inputs (DUAO), silvopastoral systems (SPS), specialization of the farm (ESPEX), water availability (AGFI), soil erosion (EROS), arable layer (CAPA).

statistically significant. Together, these results underscore the complex, multidimensional nature of sustainability and highlight the value of integrated assessment frameworks in guiding the design of more resilient and productive livestock systems.

DISCUSSION

Applying a three-dimensional framework that reflects interrelations among the social, economic, and environmental dimensions, this study offers an integrative analysis of cattle farming systems. The results highlight the fundamental role of environmental variables, while also emphasizing the influence of economic and demographic factors. The identification of these variables can lay the foundation for the development of policies and interventions in the livestock sector.

A positive and statistically significant correlation was observed between economic dependence on cattle farming (DECONAG) and specialization of the farm (ESPEX) suggesting that farms that allocate a larger proportion of land to livestock tend to be more dependent on income from livestock sales. This relationship is consistent with the results of other studies that associate production specialization with greater technical efficiency and market orientation (Barrezueta-Unda, 2018; Muhamad *et al.*, 2021). However, economic dependence can increase vulnerability to market volatility or environmental factors, such as droughts, especially in systems with limited diversification (Sánchez *et al.*, 2022). In addition, the positive correlation between DECONAG and annual yield (RENA) indicates that farms that are more economically dependent on livestock also tend to generate higher levels of income. This finding not only reflects the advantages of scale and specialization, but also indicates that intensive use of inputs and labor can affect long-term sustainability if not balanced with resource conservation (Klasen *et al.*, 2016).

The analysis revealed demographic differences among producer groups. On the one hand, younger producers belonging to Group 1 saw their economic performance limited because they had significantly smaller herds and less land. However, previous research suggests that younger farmers can increase their productivity and long-term sustainability as a result of a greater willingness to innovate and adopt technology (Milone & Ventura, 2019). In contrast, older producers (Group 3) manage larger herds and land areas but may face infrastructure constraints, including reduced access to basic services. On the other hand, the positive correlation between farm specialization (ESPEX) and soil erosion (EROS) raises serious environmental concerns. Farms with a higher proportion of pasture showed greater vulnerability to erosion, probably due to topographical conditions such as slope and soil degradation in intensive grazing systems. This finding is consistent with the literature documenting the risks of erosion on steep land under continuous grazing regimes (Chen *et al.*, 2021; Sanjari *et al.*, 2009). Environmentally friendly practices such as silvopastoral systems (SPS) and rotational grazing can mitigate these impacts (Milera *et al.*, 2019). Although agricultural training (CAPAGRI) was not revealed as a statistically significant factor among the groups, its positive association with water availability (AGFI) suggests that access to technical knowledge can encourage investment in agricultural infrastructure and better resource management. Similar behaviors have been observed in other contexts, where education increases farmers' adaptive capacity and improves resource use efficiency (Zarei *et al.*, 2020).

A noteworthy result is the positive correlation between water availability (AGFI) and soil erosion (EROS), indicating that access to water—while beneficial— can also drive overgrazing or inadequate pasture management, increasing soil erosion. Therefore, integrated resource planning is necessary, combining access to water with soil conservation measures and sustainable forage use (Chen *et al.*, 2021). Similarly, integrating trees, shrubs, and livestock into silvopastoral systems contributes to improving soil structure, increasing organic matter, and reducing erosion through root stabilization (Huertas *et al.*, 2021; Murgueitio *et al.*, 2013), which was observed in the positive correlation between SPS and topsoil depth (CAPA). These systems not only improve environmental sustainability, but also promote animal welfare and resilience to climate stressors (Murgueitio *et al.*, 2013). The weak and nonsignificant negative correlation between AGE and access to basic services (SERB) suggests that older producers may be underserved. This is alarming and should be addressed as a priority through rural policies, as aging populations often face barriers to accessing services that are essential for well-being and productivity (Gu *et al.*, 2023; Superintendencia Nacional de Salud, 2023).

Public Policies and Interventions Based on the Identified Indicators

It is essential that interventions and policies take heterogeneity into account to ensure equitable access to public services, healthcare, and market infrastructure for rural populations of all ages. While improving living standards and service availability is desirable, implementation must be context-appropriate. Previous studies have shown that biodiversity and ecological functions could be compromised if changes in land use and infrastructure development are not planned in a sustainable manner (Barrezueta-Unda, 2018; Varijakshapanicker *et al.*, 2019).

From a policy perspective, ecological vulnerability and accessibility to services must be addressed by adopting a territorial approach that takes into account the heterogeneity of production systems. In order to avoid unwanted environmental degradation, in areas with abundant water resources where the risk of erosion is evident, policies should incorporate incentives for soil conservation, which in turn can drive infrastructure development (Chen *et al.*, 2021; Sanjari *et al.*, 2009). To achieve this, intersectoral coordination between environmental, agricultural, and rural development institutions is required.

Rather than targeting large groups of producers, policies should support knowledge transfer and capacity building in a personalized manner. Similarly, younger producers have shown greater potential for innovation and adoption of sustainable practices (Milone & Ventura, 2019), despite their limited assets in terms of land and capital. In this context, interventions must be integrated into a territorial development framework that simultaneously addresses ecological vulnerability and demographic transitions. Empowering younger producers, especially in rural areas where livestock farming continues to predominate, can encourage generational renewal, increase productivity, and contribute to the development of more resilient and inclusive livestock systems. In addition, specific investments in rural infrastructure and social support are needed to address deficiencies in services provided to older producers. Consequently, policy strategies tailored to different age groups may include (1) incentives tailored to the age and needs of the producer, preferential agricultural loans, or tax exemptions; (2) training programs and improved access to digital tools, including automation, the Internet of Things (IoT), and remote sensing; (3) the creation of rural innovation programs to promote entrepreneurship and knowledge sharing; and (4) systems that reward the adoption of sustainable practices. At the institutional level, it is essential to provide information that allows for adjustments to policies that incorporate both public and private participatory elements to establish a monitoring and evaluation system to track the programs implemented.

Finally, this study recognizes the inherent limitations of sustainability assessments. The multidimensional nature of the concept requires context-specific selection of indicators and careful weighting. In addition, regional heterogeneity, both ecological and socioeconomic, requires adaptive approaches to sustainability assessment. A key area for future research is the optimization of water management strategies, given that water availability has become both a limiting factor and a source of environmental risk. In addition, future research could consider the implementation of socioeconomic and environmental zoning for the development of productive activities.

CONCLUSION

This study confirmed the hypothesis that cattle farming systems with higher specialization, economic performance, access to basic services, and adoption of ecological practices tend to be more sustainable. In particular, six key indicators were identified as determinants of sustainability in cattle farming systems: producer age, economic dependence on cattle farming, annual yield, specialization of the farm, water availability on the farm, and soil erosion. These findings lay the groundwork for designing specific public policies that account for the structural and contextual heterogeneity of production systems while promoting more sustainable cattle farming systems.

CONFLICT OF INTERESTS

The authors declare that the research was conducted without any commercial or financial relationships that could be construed as potential conflicts of interest.

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DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the authors used Chat GPT in order to improve readability and language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

REFERENCES

Bacon, C. M., Getz, C., Kraus, S., Montenegro, M., & Holland, K. (2012). The social dimensions of sustainability and change in diversified farming systems. Ecology and Society, 17(4), 41. https://doi.org/10.5751/ES-05226-170441

Barrezueta-Unda, S. A. (2018). Construcción de indicadores agrarios para medir la sostenibilidad de la producción de cacao en el Oro, Ecuador. Retrieved February 23, 2024, from https://core.ac.uk/download/pdf/154757523.pdf

Ben-Eli, M. U. (2018). Sustainability: definition and five core principles, a systems perspective. Sustainability Science, 13(5), 1337–1343. https://doi.org/10.1007/s11625-018-0564-3

Benitez-Altuna, F., Trienekens, J., & Gaitán-Cremaschi, D. (2023). Categorizing the sustainability of vegetable production in Chile: a farming typology approach. International Journal of Agricultural Sustainability, 21(1). https://doi.org/10.1080/14735903.2023.2202538

Biswas, B., Singh, A., Rai, P. K., Kumar, J., & Walker, S. (2022). GIS based study of reclamation of degraded semi-arid soil: a case study from Rajasthan, India. Indian Journal of Environmental Protection, 42(3), 302–315.

Bousbia, A., Gueroui, Y., Aouadi, A., Teweldebirhan, M. D., Bessa, R. J. B., Symeon, G., & Boudalia, S. (2024). Typology analysis of cattle farms in Northeast Algeria: Potential for sustainable development. Agricultural Systems, 218(June), 103995. https://doi.org/10.1016/j.agsy.2024.103995

Bragaglio, A., Romano, E., Brambilla, M., Bisaglia, C., Lazzari, A., Giovinazzo, S., & Cutini, M. (2023). A comparison between two specialized dairy cattle farms in the upper Po Valley. Precision agriculture as a strategy to improve sustainability. Cleaner Environmental Systems, 11(September), 100146. https://doi.org/10.1016/j.cesys.2023.100146

Chen, J., Li, Z., Xiao, H., Ning, K., & Tang, C. (2021). Effects of land use and land cover on soil erosion control in southern China: Implications from a systematic quantitative review. Journal of Environmental Management, 282, 111924. https://doi.org/10.1016/j.jenvman.2020.111924

Cirella, G. T., & Russo, A. (2020). Special issue sustainable interdisciplinarity: Human-nature relations. Sustainability, 12(1), 10–14. https://doi.org/10.3390/su12010002

Escribano, A. J., Gaspar, P., Mesías, F. J., Pulido, A. F., &

Escribano, M. (2014). A sustainability assessment of organic and conventional beef cattle farms in agroforestry systems: The case of the "dehesa" rangelands. ITEA Informacion Tecnica Economica Agraria, 110(4), 343–367.

FAO. (2025). Producción animal. Retrieved January 12, 2025, from https://www.fao.org/animal-production/es/#:~:text=El ganado contribuye a casi el 40%25 de,suministro mundial de proteínas alimentarias procede del ganado.

Fernández, P. D., Gasparri, N. I., Rojas, T. N., Banegas, N. R., Nasca, J. A., Jobbágy, E. G., & Kuemmerle, T. (2024). Silvopastoral management for lowering trade-offs between beef production and carbon storage in tropical dry woodlands. Science of the Total Environment, 912, 168973. https://doi.org/10.1016/j.scitotenv.2023.168973

Gobierno regional de Cajamarca. (2023). Cajamarca alberga a más de 755 mil vacunos y registra el 17,5% de producción lechera a nivel nacional. Retrieved December 1, 2024, from 22-11-2023 website: https://www.gob.pe/institucion/regioncajamarca/noticias/935907-cajamarca-alberga-a-mas-de-755-mil-vacunos-y-registra-el-17-5-de-produccion-lechera-a-nivel-nacional

Gómez Urrutia, V., & Jiménez Figueroa, A. (2015). Corresponsabilidad familiar y el equilibrio trabajo-familia: medios para mejorar la equidad de género. Polis, 14(40), 377–396. https://doi.org/10.4067/S0718-65682015000100018

Gu, B., Ren, C., Zhou, X., Wang, C., Guo, Y., Diao, Y., Shen, S., Reis, S., Li, W., Xu, J., & Gu, B. (2023). Aging threatens sustainability of smallholder farming in China. Nature, 616(7955), 96–103. https://doi.org/10.1038/s41586-023-05738-w

Huertas, S. M., Bobadilla, P. E., Alcántara, I., Akkermans, E., & van Eerdenburg, F. J. C. M. (2021). Benefits of silvopastoral systems for keeping beef cattle. Animals, 11(4), 1–12. https://doi.org/10.3390/ani11040992

INEI. (2023). Sistema Regional para la Toma de Decisiones. Retrieved December 8, 2024, from https://systems.inei.gob.pe/SIRTOD/app/consulta

Klasen, S., Meyer, K. M., Dislich, C., Euler, M., Faust, H., Gatto, M., Hettig, E., Melati, D., Surati, I., Otten, F., Pérez-Cruzado, C., Steinebach, S., Suria, T., & Wiegand, K. (2016). Economic and ecological trade-offs of agricultural specialization at different spatial scales. Ecological Economics, 122, 111–120. https://doi.org/10.1016/j.ecolecon.2016.01.001

Lê, S., Josse, J., & Husson, F. (2008). FactoMineR : An R Package for Multivariate Analysis. Journal of Statistical Software, 25(1). https://doi.org/10.18637/jss.v025.i01

Lohr, S. L. (2021). Sampling: Design and Analysis (3rd ed.). Chapman and Hall/CRC. https://doi.org/10.1201/9780429298899

Milera, M., Machado, L., Amaro, O., Hernández, M., & Sánchez, S. (2019). Intensive rational grazing as alternative for low-emission animal husbandry. Pastos y Forrajes, 42(1), 3–12. Retrieved from https://orcid.org/0000-0001-8531-3425

Milone, P., & Ventura, F. (2019). New generation farmers: Rediscovering the peasantry. Journal of Rural Studies, 65, 43–52. https://doi.org/10.1016/j.jrurstud.2018.12.009

Muhamad, G. M., Heshmati, A., & Khayyat, N. T. (2021). How to reduce the degree of dependency on natural resources? Resources Policy, 72, 102047. https://doi.org/10.1016/j.resourpol.2021.102047

Mulema, A. A., Jogo, W., Damtew, E., Mekonnen, K., & Thorne, P. (2019). Women farmers' participation in the agricultural research process: implications for agricultural sustainability in Ethiopia. International Journal of Agricultural Sustainability, 17(2), 127–145. https://doi.org/10.1080/14735903.2019.1569578

Murgueitio, E., Chará, J., Solarte, A., Uribe, F., Zapata, C., & Rivera, J. (2013). Agroforestería pecuaria y sistemas silvopastoriles intensivos (SSPi) para la adaptación ganadera al cambio climático. Revista Colombiana de Ciencias Pecuarias, 26, 313-316. https://doi.org/10.17533/udea.rccp.324845

Ouali, M., Belhouadjeb, F. A., Soufan, W., & Rihan, H. Z. (2023). Sustainability evaluation of pastoral livestock systems. Animals, 13(8), 1335. https://doi.org/10.3390/ani13081335

Pollesch, N. L., & Dale, V. H. (2016). Normalization in sustainability assessment: Methods and implications. Ecological Economics, 130, 195–208. https://doi.org/10.1016/j.ecolecon.2016.06.018

Porto, R. T., & Sili, M. E. (2020). Toma de decisiones y gestión productiva en el sector agropecuario del Noreste de La Pampa (Argentina). Revista de Economia e Sociologia Rural, 58(2), 1–19. https://doi.org/10.1590/1806-9479.2020.198357

Ren, C., Zhou, X., Wang, C., Guo, Y., Diao, Y., Shen, S., Reis, S., Li, W., Xu, J., & Gu, B. (2023). Ageing threatens sustainability of smallholder farming in China. Nature, 616(7955), 96-103. https://doi.org/10.1038/s41586-023-05738-w

Ruiz Méndez, D., Quezada, M. E., & Vega Valero, C. Z. (2020). Estadística robusta aplicada a las medidas de localización y escala: Nota Técnica. Revista Digital Internacional de Psicología y Ciencia Social, 6(2), 499–517. https://doi.org/10.22402/j.rdipycs.unam.6.2.2020.302.499-517

Sánchez, A. C., Kamau, H. N., Grazioli, F., & Jones, S. K. (2022). Financial profitability of diversified farming systems: A global meta-analysis. Ecological Economics, 201, 107595. https://doi.org/10.1016/j.ecolecon.2022.107595

Sandoval Yate, D. F., Triana Ángel, N., & Burkart, S. (2024). Pathways towards sustainability: A capacity needs assessment for the implementation of the Colombian Policy for Sustainable Cattle 2022–2050. Journal of Rural Studies, 112, 103472. https://doi.org/10.1016/j.jrurstud.2024.103472

Sanjari, G., Yu, B., Ghadiri, H., Ciesiolka, C. A. A., & Rose, C. W. (2009). Effects of time-controlled grazing on runoff and sediment loss. Australian Journal of Soil Research, 47(8), 796–808. https://doi.org/10.1071/SR09032

SENAMHI. (2025). Mapa climático del Perú. Retrieved February 24, 2025, from https://www.senamhi.gob.pe/?p=mapa-climatico-del-peru

Stock, P., & Burton, R. J. F. (2011). Defining terms for integrated (multi-inter-trans-disciplinary) sustainability research. Sustainability, 3(8), 1090–1113. https://doi.org/10.3390/su3081090

Superintendencia Nacional de Salud. (2023). Adultos mayores son el grupo con mayor vulneración de sus derechos en salud. Retrieved December 18, 2024, from 28 de febrero de 2023 website: https://www.gob.pe/institucion/susalud/noticias/718639-adultos-mayores-son-el-grupo-con-mayor-vulneracion-de-sus-derechos-en-salud

Torres Jara de García, G. P., Durand-Chávez, L. M., Quispe-Ccasa, H. A., Linares-Rivera, J. L., Segura Portocarrero, G. T., Calderón Tito, R., Vásquez Pérez, H. V., Maicelo Quintana, J. L., Ampuero-Trigoso, G., Robles Rodríguez, R. R., & Saucedo-Uriarte, J. A. (2023). Sustainability of livestock farms: The case of the district of Moyobamba, Peru. Heliyon, 9(2), e13153. https://doi.org/10.1016/j.heliyon.2023.e13153

Varijakshapanicker, P., McKune, S., Miller, L., Hendrickx, S., Balehegn, M., Dahl, G. E., & Adesogan, A. T. (2019). Sustainable livestock systems to improve human health, nutrition, and economic status. Animal Frontiers, 9(4), 40–49. https://doi.org/10.1093/af/vfz041

Williams, M., Murphy, C. P., Sleator, R. D., Ring, S. C., & Berry, D. P. (2021). Genetic and nongenetic factors associated with lactation length in seasonal-calving, pasture-based dairy cows. Journal of Dairy Science, 104(1), 561–574. https://doi.org/10.3168/jds.2020-18941

Zarei, Z., Karami, E., & Keshavarz, M. (2020). Co-production of knowledge and adaptation to water scarcity in developing countries. Journal of Environmental Management, 262, 110283. https://doi.org/10.1016/j.jenvman.2020.110283