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Evaluating the Breed and Production Diversity in Dual Purpose Cattle Systems in Colombia: Opportunities for Its Sustainability

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Abstract: Approximately 60% of milk production in Colombia comes from dual-purpose (DP) systems, which face limitations in defining racial composition and maintaining production records for genetic resource management in the regions. The objective of this study was to evaluate the phenotypic diversity of cattle in DP systems and generate indicators that link this diversity to productivity, contributing to sustainability in these territories. A total of 2760 animals were phenotypically classified using two criteria associated with Breed Classification (BC) and Apparent Phenotypic Predominance (APP). Linear mixed models including fixed effects of region, covariates of age of cow and days in milk, and animal as random effect, were applied to daily milk records from 2042 cows to estimate the productivity of the breed assignment criteria in the genetic resource management. Most animals (66.92%) were assigned to the Mixed genetic group because its unknown genetic origin. Based on BC the second group comprise individuals classified as Crossbred (10.72%) that exhibit known genetic origin, but their genetic management was hindered by the lack of productive information. Meanwhile, the APP criteria was relevant to describe how either zebuine or taurine breed predominance influenced the daily milk production (3.52 ± 0.76 to 5.8 ± 0.14 kg, respectively) of individuals according to the environmental offerings in the regions. When assessing the impact of phenotypic selection processes in females based on a 1 kg increase in daily milk production could raise the population's average daily productivity by 0.49 kg. However, this approach poses a risk to the inventory of Mixed animals, which have been used as a genetic resource adapted to the region for several decades.

Keywords: environment; mixed cattle; apparent phenotypic predominance; selection

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1. Introduction

Milk production worldwide plays a vital role in ensuring food security and nutrition for consumers, as well as supporting the food industry. In 2022, global milk production reached 950 million tons, with South America contributing 68 million tons. The region's largest milk producers include Brazil, Uruguay, and Peru, while Colombia, Argentina, and Chile experienced declines in production due to costs. Specifically, Colombia reported a production of 7.36 million tons in 2022 [1].

Milk production in Colombia faces significant challenges, including the need to reduce costs, improve yields, and enhance the competitiveness of the production chain [2]. Insufficient production data records in herds, along with environmental and genetic diversity, present both challenges and opportunities.

Specialized milk production systems in Colombia have successfully addressed some of these challenges by managing specialized foreign breeds and adopting technological innovations [3]. However, approximately 50% of the country's milk production systems are classified as dual-purpose (DP), where females are dedicated to milk production and males are raised for meat. DP systems are typically located in regions below 2000 m above sea level (m.a.s.l), characterized by extensive management of native pastures and low levels of technological adoption [4].

Unlike specialized systems, under 2000 m.a.s.l the environmental conditions reduce the production of specialized cattle for either high temperature [5], forage resources availability [6] or hemoparasites-driven diseases [7]. Therefore, DP systems predominantly utilize locally adapted cattle, favoring crossbreeding between *Bos indicus* and *Bos taurus* breeds to enhance productivity while maintaining adaptation to harsh climatic conditions.

Dual-purpose cattle systems offer a sustainable approach by optimizing resource use while providing economic stability through diversified products (milk and meat) for rural families in a wide range of agricultural environments. Additionally, opportunities to enhance reduction in greenhouse gas emissions, soil health and carbon sequestration [8] could be enhanced across implementation of adequate manage practices.

Despite these advantages, the low level of technological adoption and absence of production records limit competitiveness. This includes the undefined genetic composition of herds [9], insufficient data to guide production aligned with environmental resources [10], and challenges in meeting formal market standards for fresh or processed products [11].

DP systems often experience slow productivity gains, as the adoption of advanced technologies requires significant investments that many producers cannot afford [12]. However, the implementation of "soft technologies", such as milk production records and the identification of genetic resources, can serve as foundational steps toward the eventual integration of "hard technologies" within a well-defined production framework [13]. Moreover, a comprehensive understanding of productive diversity and its relationship with environmental resources could enhance market access for milk quality standards [14] and sustainability.

In this context, this study aimed to assess the phenotypic diversity of cattle within DP systems in the department of Huila, Colombia. Additionally, the study sought to develop indicators that establish links between phenotypic diversity, productivity, and sustainability within these production systems.

2. Materials and Methods

2.1. Ethical Approval

This study was conducted following the approval of the Ethics, Bioethics, and Scientific Integrity Committee of the Corporación Colombiana de Investigación Agropecuaria—AGROSAVIA (Act No. 2 of 2021).

2.2. Study Area and Population

The study was carried out on 206 farms across 24 municipalities in the department of Huila, Colombia. These municipalities were grouped into four geographic zones that reflect differences in environmental conditions within the department (Table 1).

Table 1. Distribution of evaluated farms and animals across zones in the department, along with altitude and temperature ranges of the municipalities studied.

Geographical Zone	Municipalities	Herds	Animals	Range Average Temperature (°C)	Range Average Altitude (m.a.s.l)
North	10	87	1108	24–28.6	384–1900
Central	6	50	663	23–25	826–1079
West	4	41	655	20–26	830–1418
South	4	28	334	18–24	1100–1730

The farms were selected in collaboration with livestock associations recognized by institutional authorities. Each farm was required to have certified vaccination records and adequate facilities for collecting milk production data.

2.3. Breed Classification of Individuals

A total of 2760 lactating cows were identified on the farms (13.39 ± 10.3 cows/farm). Among them, 2042 had information on their last calving date, which was used to determine the lactation day at milk recording. Due the lack of records in several herds, information on the lactation number was unavailable. However, data on individual age were recovered and used as an indicator of their physiological stage. During the initial visit to each farm, trained technical personnel conducted a visual inspection of the animals to establish the primary genetic composition based on their phenotype. Due to the absence of records, the potential genealogy of the animals could not be verified.

To classify the animals in dual-purpose (DP) systems, two strategies were used:

Breed Classification (BC): animals were assigned to four main genetic groups (Crossbred, Mixed, Zebuine, Taurine) based on farm records (genealogy, animal origin) and the expertise of the technical trained personnel.

Apparent Phenotypic Predominance (APP): this approach assesses distinct phenotypic traits to either identify the zebuine and taurine origin or to determine whether an animal predominantly exhibited zebuine or taurine characteristics [9].

Using this method, six genetic groups were identified: Crossbred, referring to individuals associated with well-defined breeds such as Girolando; Mixed, encompassing individuals with no distinctive zebuine or taurine phenotype or unknown genetic origin; Zebuine, including Brahman, Guzerat, and Gyr breeds; and Taurine, which comprised individuals of well-defined taurine origin, such as Holstein, Jersey, and the Colombian Creole breed Blanco Orejinegro. Additionally, two broader categories were established: Predominantly Zebuine, for individuals exhibiting a distinctive hump, highly developed dewlap and navel, long and hairless ears, and solid gray, black, ash, or red coat colors; and Predominantly Taurine, for individuals lacking a pronounced hump, dewlap, and navel, with short and hairy ears, a coat that may be spotted or solid in colors ranging from black to red, and variable horn presence.

2.4. Milk Production Monitoring

Monthly milk production monitoring visits were conducted on each farm between April 2023 and June 2024. These visits followed the ICAR protocol for milk recording (https://www.icar.org/index.php/icar-recording-guidelines/, accessed on 21 December 2024), specifically using method AP44, 1x. Trained technical personnel ensured standardized data collection, measurement, and sample acquisition. Milk production was recorded for each animal during the morning milking using an FF1976 MODEL 14191-744E electronic scale. All measurements were consolidated and validated into the project database.

2.5. Statistical Analysis

The breed assignment of the population was assessed using both BC and APP criteria. The Shannon diversity index $H' = -\sum_{i=1}^{s} p_i ln(p_i)$ [15], where, p is the proportion of individuals from the i breed or species in the s breeds or species observed in the community, was calculated for each classification to evaluate differences in the observed genetic proportions across regions. Additionally, a Chi-squared test was performed to determine significant differences in the genetic group proportions among regions.

Milk production analysis was based on 14,774 field measurements (6.67 daily records/animal). Only records from animals with at least three milk monthly records during their lactation period (measured between days 5 and 300 postpartum) were considered. Data were validated for normality, and outliers (below to 1 kg or upper than 20 kg) were excluded following ICAR recommendations (Section 2). Finally, 11,679 daily milk records were retained for further analysis.

Daily milk production records were analyzed using linear mixed models. Fixed effects included the region within the department (North, Central, West, and South; Table 1) and breed assignment criteria (BC and APP). Lactation day at the time of measurement and age of animal were included as a covariate. Considering the use of multiple milk records per animal (repeated measurements), the variability within individuals was treated as a random effect. Modeling was conducted using the lme function from the nlme package [16] in R software v4.4.1 [17]. The Tukey test was used for pairwise comparisons of adjusted means of fixed effects implemented in the emmeans library [18]. Model performance for BC and APP criteria was performed using a likelihood ratio test to determine the best fit.

Finally, based on the distribution of daily milk records observed in this study, along with the forage resources and management practices identified in the herds, increasing daily milk yield by at least 1 kg per day presents a significant challenge. Therefore, changes in productivity and genetic diversity were evaluated by applying a phenotypic selection criterion, retaining females with average daily milk production thresholds ranging from 2 to 5 kg. Descriptive statistics were calculated for milk production in animals meeting each threshold. Changes in genetic groups proportions under selection were compared across regions using the Chi-squared test. Data processing, mixed-model analysis, and Chi-squared tests were performed in R [17].

3. Results

3.1. Evaluation of Breed Diversity

Dual-purpose (DP) systems are characterized by low technological adoption. In this study, only 20 out of 206 (9.7%) farms visited had any genealogical records, but insufficient for reliable breed identification.

Field-based phenotypic evaluations combined with producer-provided information enabled the identification of predominant genetic groups in 2760 animals from the sampled farms. As expected, the majority (66.92%) of animals were classified as Mixed, with their genetic origins largely unknown. This genetic group, commonly referred to as "Siete Colores" (Seven Colors), by their multibreed composition, was observed in 183 of the 206 farms evaluated.

The second group consisted of Girolando animals (10.72%), followed by Gyr (4.27%), Jersey (3.36%), Brown Swiss (2.75%), and Holstein (1.84%). The remaining 10.14% of the population included Ayrshire, Brahman, Blanco Orejinegro, and Crossbred animals. Notably, the study identified small numbers of Simmental (0.43%, n = 12), Angus (0.21%, n = 6), and Swedish Red (0.03%, n = 1) animals.

The Shannon Diversity Index revealed the highest breed diversity in the south region (H′ = 1.78), followed by the central (H′ = 1.52), west (H′ = 1.22), and north regions (H′

= 1.18). The south region, characterized by a stronger emphasis on dairy production, exhibited 14 genetic groups primarily associated with taurine dairy breeds. Of these, Mixed and Girolando animals accounted for 59.88% of the population, while Gyr, Jersey, Blanco Orejinegro, and Jersey × Holstein represented an additional 36.82%.

In contrast, the north region, which experiences higher temperatures (Table 1), displayed 28 genetic groups. Mixed and Girolando animals were the more frequent groups, accounting for 81.22% of the population. These were followed by Gyr, Brahman, and six additional breeds, comprising 96.93% of the regional population.

According to producers, the majority of the population (74.92%) was reported to have zebuine ancestry, with the remaining 25.07% being taurine. The lack of production records limited precise identification of genetic components. To address this, animals were grouped using two strategies: Breed Classification (BC) and Apparent Phenotypic Predominance (APP).

Using BC, 6.70% of animals were classified as Zebuine, 12.25% as B. taurus × B. indicus Crossbreds, 66.92% as Mixed animals, and 11.12% as Taurine. Significant differences were observed in the distribution of BC-defined groups across regions (X^2 = 130.86, df = 9, $p < 2.2 \times 10^{-16}$; Figure 1). This suggests that breed distribution is influenced by regional factors such as environmental conditions, management practices, and producer preferences.

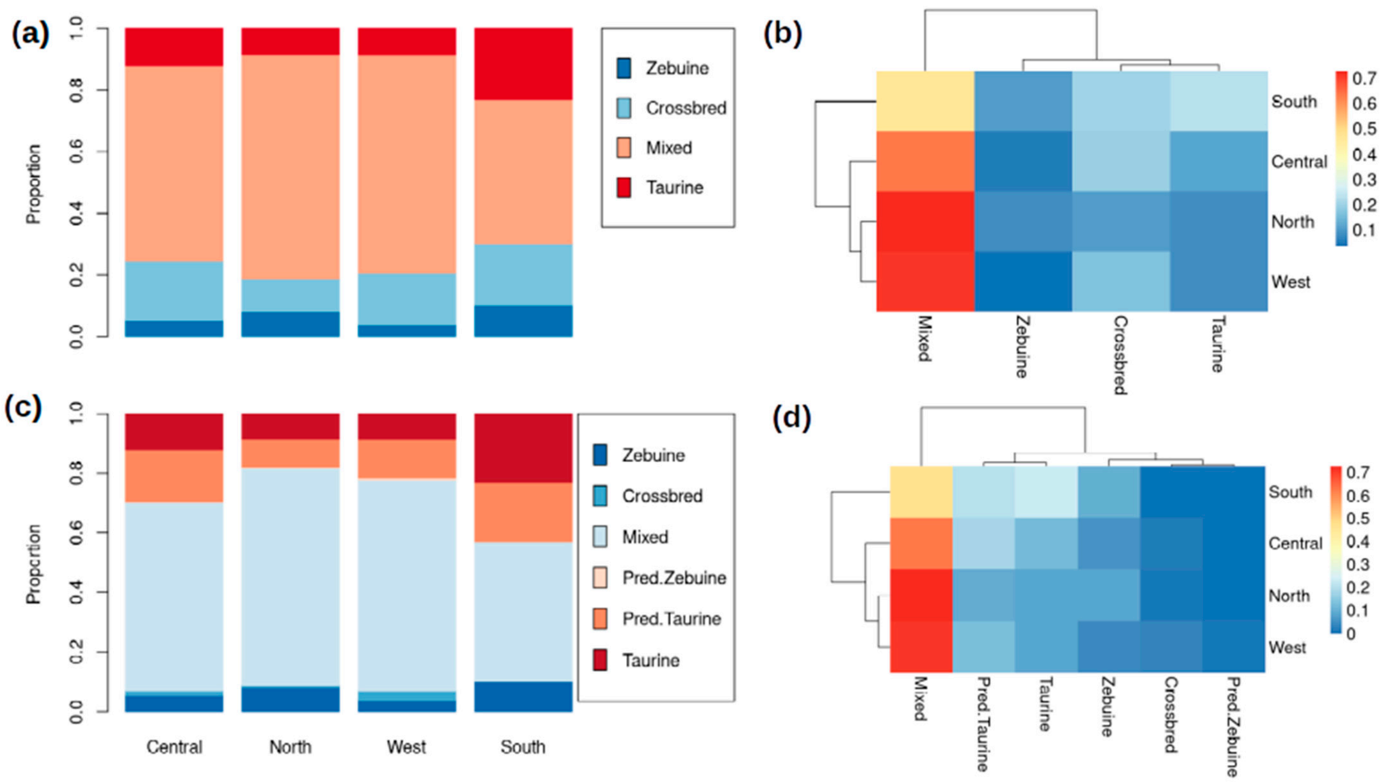

Figure 1. Proportions of individuals by breed classification and regional distribution: (**a**) Proportion of individuals by BC in each region, (**b**) Regional variation in BC, (**c**) Proportion of individuals by APP, (**d**) Regional variation in APP.

The Shannon Diversity Index further highlighted regional differences in genetic diversity. The southern region exhibited the highest diversity (H′ = 1.25), indicating a more balanced representation of genetic groups (Figure 1a). The central region (H′ = 1.02) displayed moderate diversity, while the north (H′ = 0.88) and west (H′ = 0.87) regions showed lower diversity, reflecting the dominance of certain genetic groups.

The heatmap (Figure 1b) supports these findings, clustering the north and west regions together based on lower breed diversity, and separated from the central and southern regions. The widespread prevalence of the Mixed group underscores the need for tools like molecular markers to better characterize this population in tropical environments.

The APP strategy allowed for the classification of individuals based on expected breed proportions different either from 0.5 or 1.0, for zebuine or taurine groups, with productivity influenced by the prevailing environmental conditions.

Under this classification, 6.70% of animals were Zebuine, 0.36% Predominantly zebuine, 1.41% *B. taurus* × *B. indicus* Crossbreds, 13.47% Predominantly taurine, and 11.12% Taurine. Mixed animals were treated as a separate genetic group. Significant differences were also found in the distribution of APP-defined groups across regions ($X^2 = 159.72$, df = 15, $p < 2.2 \times 10^{-16}$).

The Shannon Diversity Index for APP-based groups revealed regional differences. Notably, the south region maintained the highest diversity (H′ = 1.25), reflecting again the balanced representation of taurine-predominant phenotypes in crossbred populations. The central region showed moderate diversity (H′ = 1.08). In contrast, the west region exhibited higher diversity (H′ = 0.98) compared to BC, due to reclassification of 85 out of 110 crossbred animals as Predominantly taurine, while 20 remained crossbred and five were Predominantly zebuine. The north region also showed a slight increase in diversity (H′ = 0.92), primarily due to reclassification of 104 out of 117 crossbred animals as Predominantly taurine, mostly Girolando.

3.2. Milk Production Analysis

After refining the database, milk production data from 2042 animals were analyzed. The average age of cows under observation was 72.53 ± 27.38 months, ranging from 29 to 180 months, contributing significantly ($p < 0.01$) in the milk production. Average daily milk production was 5.07 ± 2.59 kg, with records ranging from 1 to 16 kg/day. A significant decrease in milk production was observed with age increase ($p < 0.001$; Figure 2). Notably, 25% of the evaluated population was over 85 months old, emphasizing the need for replacement planning to enhance production efficiency and sustainability.

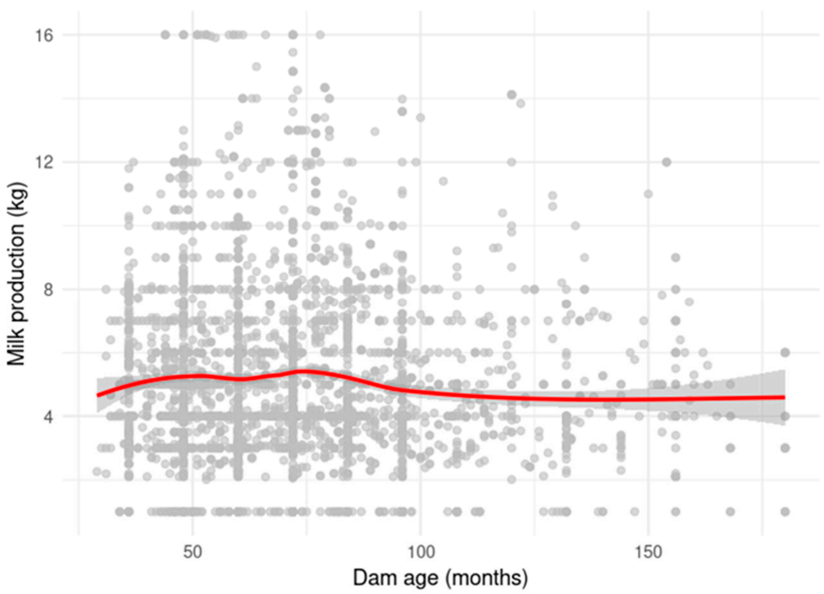

Figure 2. Distribution of daily milk production regarding the age of cow. Red line represents the average daily milk production.

Daily milk production was evaluated using mixed models, independently considering BC and APP breed classifications. In both models, the fixed effect of region and the covariates days in milk (DIM) and age of cows significantly influenced daily milk production ($p < 0.05$; Table 2).

Table 2. Adjusted means, standard errors, and confidence intervals for daily milk production (kg) by region and breed classification.

Model	Effect	Level	Mean ± S.E.	Lower CL	Upper CL	*p* Value
BC	Overall		5.15 ± 0.09	4.98	5.32	
	DIM		−0.0048 ± 0.0002			<0.001
	Age of cow		−0.0064 ± 0.0017			<0.001
	Region					<0.001
		Central	4.85 ± 0.12 a	4.61	5.09	
		North	5.01 ± 0.14 a	4.74	5.28	
		West	5.12 ± 0.13 ab	4.87	5.37	
		South	5.64 ± 0.2 b	5.25	6.03	
	Breed Classification					<0.001
		Zebuine	4.53 ± 0.25 a	4.05	5.02	
		Crossbred	5.69 ± 0.13 b	5.43	5.94	
		Mixed	4.93 ± 0.09 a	4.74	5.11	
		Taurine	5.46 ± 0.16 b	5.14	5.78	
APF	Overall		4.93 ± 0.15	4.62	5.23	
	DIM		−0.0048 ± 0.0002			<0.001
	Age of cow		−0.0064 ± 0.0017			<0.001
	Region					<0.001
		Central	4.61 ± 0.18 a	4.26	4.96	
		North	4.8 ± 0.19 ab	4.43	5.16	
		West	4.92 ± 0.17 ab	4.57	5.26	
		South	5.38 ± 0.24 b	4.90	5.85	
	Breed Classification					<0.001
		Zebuine	4.53 ± 0.25 a	4.04	5.02	
		Crosbred	5.32 ± 0.38 ab	4.58	6.06	
		Mixed	4.92 ± 0.09 ab	4.73	5.10	
		Pred. Zebuine	3.52 ± 0.76 a	2.04	5.01	
		Pred. Taurine	5.8 ± 0.14 b	5.53	6.07	
		Taurine	5.46 ± 0.16 b	5.14	5.78	

ab: Different letters represents significant statistical differences ($p < 0.05$).

As expected, the DIM had a highly significant effect ($p < 0.01$), consistent with lactation physiology, where average milk production decreases by 0.0048 kg per day. Adjusted milk production ranged from 4.93 ± 0.15 to 5.15 ± 0.09 kg/day across different breed classifications.

In the BC model, the region significantly influenced milk production ($p < 0.05$), with the south region standing out at 5.64 ± 0.2 kg/day. Within breed composition, despite the Mixed genetic group had the higher proportion of individuals assigned, did not show the highest production. Crossbred and taurine animals exhibited significantly higher mean daily milk production ($p < 0.05$).

In the APP model, breed classification was more detailed, accounting for proportions that highlight Taurine or Zebuine predominance. Here, similar to the BC model, the south region excelled in milk production (5.38 ± 0.24 kg/day). This region has a strong focus on milk production, with a large inventory of Predominantly taurine animals and the lowest proportion of Mixed animals (Figure 1). Additionally, it features environmentally favorable conditions.

The APP classification allowed for the identification of more genetic groups, highlighting the productive contribution of breeds such as Girolando, which constitute a significant fraction of genetic resources in regions like northern Huila. The average daily milk production for Predominantly taurine and Taurine genetic groups (5.8 ± 0.14 and 5.46 ± 0.16 kg/day, respectively) underscored their superior productivity under the environmental offer. These groups include breeds of interest such as Jersey and Holstein, as well as Colombian creole breed Blanco Orejinegro.

Interestingly, the variability observed in the Mixed genetic group positions it as an intermediate productivity group. Strengthening the evaluation scheme for this population is essential, given its environmental adaptability and productivity.

In both BC and APP models the interaction between region and breed classification was evaluated, but no significant effect was found ($p > 0.05$). However, adjusted daily milk production revealed a trend of higher production across all genetic groups in the southern region (Figure 3).

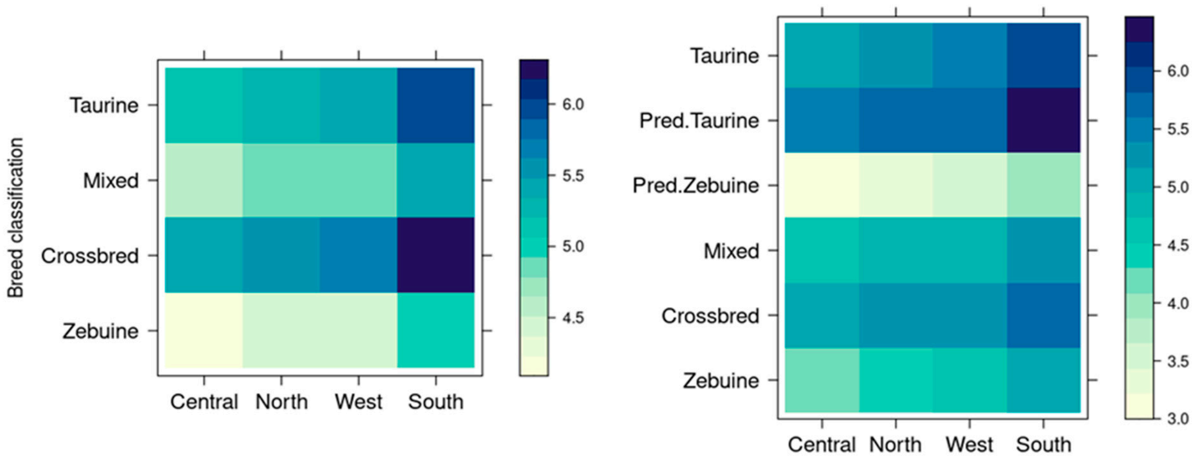

Figure 3. Daily milk production for each breed classification in the evaluated regions. (**Left**) BC classification; (**Right**) APP classification.

The Akaike Information Criterion (AIC_{APP} = 32,057.53 and AIC_{BC} = 32,064.67) and the Likelihood Ratio Test (LRT = 11.1377, p = 0.0038) showed that the APP model, with its more detailed breed classification, provided better insights into modeling daily milk production.

3.3. Population Selection Recommendations

Currently, genetic management in the population is primarily dictated by access to genetic resources. The results underscore the importance of indicators to enhance genetic management and define a consistent productive objective.

To assess the impact of a selection and multiplication scheme for females in the population, milk production and breed group composition were evaluated using productive thresholds ranging from 2 to 5 kg of milk per day (Table 3).

Table 3. Mean and confidence intervals for daily milk production in phenotypically selected females.

Selection Criteria Threshold	Mean ± S.E. Milk Production (kg) in Selected Females	Confidence Interval (kg)	Number of Selected Females Selected
No selection	5.02 ± 0.05	4.92, 5.12	2042
DMY ≥ 2	5.21 ± 0.05	5.11, 5.31	1940
DMY ≥ 3	5.54 ± 0.05	5.44, 5.64	1724
DMY ≥ 4	6.23 ± 0.05	6.13, 6.33	1295
DMY ≥ 5	6.96 ± 0.06	6.84, 7.08	914

DMY = Daily Milk Yield.

To date, genetic management is largely influenced by access to genetic resources in the regions. If strategies for multiplying females producing over 2 kg/day of milk are implemented, a mean phenotypic change of 0.49 ± 0.071 kg/day per kg of milk selection threshold is expected. Sustaining this phenotypic change over time requires evaluating environment effects and the genetic contribution of males through multibreed models or molecular data.

However, selecting females inevitably reduces the animal inventory based on production (Table 3). Under the selection criteria, changes in the proportion of individuals within BC and APP genetic groups were analyzed (Figure 4).

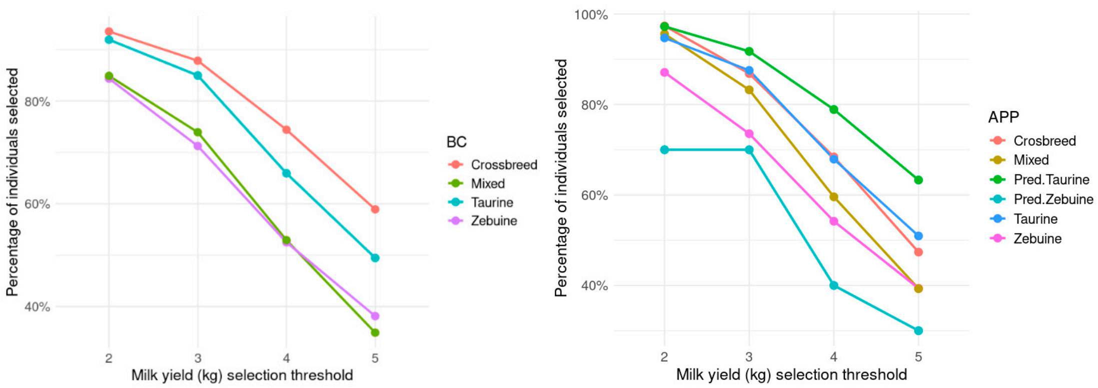

Figure 4. Changes in breed proportions based on selection recommendations using daily milk production thresholds. (**Left**) BC genetic groups; (**Right**) APP genetic groups.

In the BC model, the Chi-square test indicated significant changes ($p < 0.05$) in the proportions of each genetic group. The Mixed ($X^2 = 338$, p-value = 6.86×10^{-73}) and Taurine ($X^2 = 41.3$, p-value = 5.52×10^{-9}) groups exhibited the greatest decline in population inventory.

Similarly, in the APP classification, significant changes ($p < 0.05$) were observed for the same genetic groups: Mixed ($X^2 = 338.0$, p-value = 6.86×10^{-73}) and Taurine ($X^2 = 41.3$, p-value = 5.52×10^{-9}). Both breed classification criteria indicated that the Mixed genetic component could be at risk under selection processes, highlighting the need to understand its environmental adaptability to promote its use in scenarios with defined objectives, considering its contribution to the genetic resource inventory of the department.

4. Discussion

Dual-purpose (DP) systems should be regarded as highly significant study areas, particularly in tropical environments. These systems are not only a source of genetic variation in cattle but also shaped by various environmental and management factors that influence their adaptation and long-term sustainability [19,20].

In Colombia, the DP system contributes approximately 60% of the total milk production in the country [4] and is crucial for the livelihood and food security of thousands of families [1].

The development of these systems in Colombia has spanned several decades, accompanied by significant advances in cattle breeding and forage management [21]. However, it is evident that the lack of technological advancement and access to well-adapted genetic resources has led to the expansion of herd sizes without a corresponding increase in productivity [22]. The results of this study will provide considerations about the genetic resource management to gradually enhancing milk production while simultaneously improving environmental conditions are also required. These measures aim to boost productivity without compromising the cost-benefit ratio of technology implementation.

4.1. Evaluation of Genetic Diversity

Considering the extensive genetic diversity of cattle in Colombia—ranking first in Latin America [23]—it is essential to link this diversity to productive outcomes. This study explored the role of genetic diversity in enhancing the sustainability of DP systems. The introduction of foreign breeds in complex environmental settings often hinders the expected development of cattle [6]. Therefore, the lack of defined breed composition can undermine the long-term sustainability of these systems. Reports on DP system evaluations in Colombia have mainly focused on productivity [4] or management practices [2], while phenotypic and molecular analyses remain limited [9]. In most cases, the lack of breed information has led to uncertainty regarding herd breed composition, directly impacting strategies for managing heterosis and inbreeding. Further efforts to enhance pedigree management or molecular analysis are essential for long-term sustainability, given the decline in income per unit of inbreeding observed in dairy cattle [24] and the limited economic benefits derived from heterosis in crossbreeding [9].

The largest genetic group in the population was Mixed, comprising 66.92%, resulting from crossbreeding strategies mainly dependent on the availability of sires in various regions. Interestingly, the next most common genetic groups were Girolando (10.72%), Gyr (4.27%), and Jersey (3.36%). Crossbreeding between taurine and zebuine breeds is common to enhance both productivity and adaptability. A recent study in Costa Rica found that crossbred animals outperformed purebred Gyr and Brahman cattle by over 3% in reproductive traits [25]. The introduction of Gyr × Holstein crosses in Colombia has sparked interest, offering potential for high productivity in hot and humid conditions.

Given the high breed diversity and limited information, it is crucial to establish classification criteria to group animals for evaluating productive traits. In this study, assigning animals criteria (BC and APP) allowed for the identification of diversity indicators linked to geographic regions (Figure 1), helping to describe population dynamics [26]. The Southern region exhibited the greatest genetic diversity in the department, not due to the number of breeds but because of the homogeneity in the population sizes. In contrast, the Northern region faced environmental constraints that limited specialized breeds and resulted in a greater number of genetic groups (crossbreeds), which were underrepresented in the overall population.

The Apparent Phenotypic Predominance (APP) allowed for an evaluation of the phenotypic diversity of the population and its relationship to productive performance under different environmental conditions, facilitating management recommendations [9]. However, molecular tools such as SNP markers could confirm ancestry relationships and provide insights for genomic-based breeding recommendations.

4.2. Milk Production Analysis

A significant challenge for DP systems is the generation and management of production records. In Latin America and other tropical regions, smallholder decisions are often based on experience rather than data [27,28]. This study observed that only 9.7% of producers keep production records. While some reports suggest varied levels of records [29,30] comprehensive data management is not yet common practice, despite its importance for decision-making.

Milk production in DP systems in Colombia generally ranges from 4.59 to 4.9 L per day [22,31,32] with the present study reporting an average of 4.93 $\pm$ 0.15 and 5.15 $\pm$ 0.09 kg/day. Despite environmental differences, DP systems in Colombia show similar productivity levels. This suggests that strengthening these systems with a strategic development framework could improve efficiency and sustainability, reducing the vulnerability to external factors [29]. The evaluated region encompasses diverse environmental and geographic conditions (Table 1), strongly influenced by climatic phenomena such as *El Niño* and *La Niña*. For instance, most of the North region is situated below 1000 m.a.s.l., where recent *El Niño* events negatively impacted livestock production. In contrast, the South region experiences more favorable climatic conditions for animal maintenance.

Across all regions, the adoption of reproductive biotechnologies remains low, forage resources are limited in both quality and quantity, and disease prevalence is high [20]. The implementation of improved technologies could enhance both productivity and sustainability. In fact, the adoption of improved pastures and fertilization has been estimated to reduce the carbon footprint of DP systems by 25 to 48% [33]. However, most DP herds are small (<50 animals) and operate with minimal technological input, making it challenging to adopt pasture improvement or fertilization strategies [32].

The Southern region demonstrated the highest milk production, driven by a greater proportion of Taurine or Predominantly Taurine animals. The Girolando breed, largely taurine, contributed significantly to this performance, with reported milk yields of 6.7 to 7.3 L [34,35], similar to the results observed in this study. The Gyr breed also performed well in terms of productivity and adaptation, benefiting from selection criteria and genomic improvements for both milk and meat traits [36].

Notably, the Mixed group exhibited intermediate production levels. This underscores the importance of implementing regular performance monitoring to design optimal breeding strategies that can enhance the sustainability and productivity of DP systems [37]. Molecular tools and biotechnology for reproduction could greatly support these efforts.

4.3. Recommendations for Population Selection

Indiscriminate crossbreeding in DP systems often results in poor adaptation to local ecosystems and reduced productivity, as observed with the zebuine-dominant group, which consisted of animals from Guzerat $\times$ Brahman crosses with very low milk production.

The lack of population characterization and standardized production methods limits the ability to propose targeted breeding programs. This study represents an initial effort to identify animals that are well-adapted to regional conditions and could serve as valuable genetic resources for breeding programs. Directed breeding in DP systems presents a crucial opportunity to identify and improve productive traits, contributing to the country's milk production. Molecular evaluation methods could further strengthen the phenotypic strategies outlined here [38].

Collecting productive data from herds is essential, as it provides the necessary tools for identifying optimal breeding pairs. For instance, while the Gyr breed is known for its high productivity in South America, genotype-environment interactions significantly affect the performance of bulls used in both Brazil and Colombia [39]. These authors suggest evaluating environmental factors before selecting bulls.

Given the current population dynamics, an initial step was to evaluate females phenotypically and establish selection thresholds to project expected milk production for the population. The selection of females by productivity threshold indicated that for every additional kg of milk per day selected, the average population yield could increase by approximately 0.5 kg/day.

However, selecting or culling females would significantly reduce the population of Mixed and Taurine genetic groups. These groups are critical in breeding programs due to their genetic diversity and may harbor favorable genetic traits for both productivity and adaptation [40].

While this approach does not account for additive and non-additive genetic effects, as well as heterosis in crossbred animals [41] it provides an initial framework for recommendations on selecting or culling females, particularly for the Mixed group, which, alongside Taurine animals, showed the greatest likelihood of being culled due to low production.

5. Conclusions

The results of this study demonstrate the significant breed variability within dual-purpose (DP) systems across regions and their potential to ensure the sustainability of farming families in Colombia.

It is essential to accelerate knowledge transfer actions and the management of on-farm production data to strengthen decision-making regarding crossbreeding or inbreeding in accordance with environmental offerings.

The assignment of breed composition by APP criteria provided evidence of the superior productive performance of DP system animals, highlighting taurine breeds and the Southern region as the productive core of the department. It also revealed the intermediate productivity of the Mixed genetic group, whose high productive variability could lead to a reduction in its population size if female selection is implemented.

The selection of females by productivity threshold indicated that for every additional kg of milk per day selected, the average population yield could increase by approximately 0.5 kg/day. However, it also requires an improvement of resources and management practices in herds.

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Institutional Review Board Statement: The animals used in this study received handling and treatment under qualified veterinary supervision following the animal experimentation rules described in the International Guiding Principles for Veterinary Research Involving Animals. The owners of animals provided informed consent before their inclusion, and personal or farm information was treated according to habeas data Colombian laws. This study was approved by the Ethics, Bioethics, and Scientific Integrity Committee of the Corporación Colombiana de Investigación Agropecuaria Agrosavia, under Act N.2; date of approval: 6 October 2021. The herd management data were registered after the approval of farmers, and the subsequent commitment document was signed under the requirement of Corporación Universitaria del Huila Corhuila and the biotechnology project BPIN 2021000100300.

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