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Nutritional characterization of tree and shrub species for silvopastoral systems in a Colombian Andean-Amazon region

Caracterización nutricional de especies arbóreas y arbustivas para sistemas silvopastoriles en una región andino-amazónica colombiana

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ABSTRACT

Livestock farming in the Colombian Andean-Amazon region is characterized by its low competitiveness and its negative socio-environmental impact, being a factor of deforestation at national level and contributing to the generation of greenhouse gases. Silvopastoral systems (SPS) are a strategy to reduce this impact. This investigation was conducted aiming to identify and perform the nutritional characterization of tree and shrub species relevant to SPS in the Andean-Amazon region of Alto Putumayo. A diagnosis was carried out through semi-structured surveys, field visits, and knowledge dialogue sessions, recognizing potential species and their uses. For the nutritional characterization of the forage, the samples were analyzed in the laboratory using Near-Infrared Spectroscopy- NIRS technology. Subsequently, a statistical analysis was performed using an unsupervised machine learning technique based on principal component analysis. Hierarchical clustering using Ward's method identified 38 woody species with different growth habits (shrubs and trees), distributed across 20 families, mainly Asteraceae, Fabaceae, and Moraceae. Approximately 60% of the identified species are relevant in animal nutrition. The species with the best nutritional quality were *Sapium stylare, Sambucus nigra, and Tithonia diversifolia*. Likewise, four groups were determined, where the first two groups account for 79.1% of the variance. Collectively, our findings indicated that Alto Putumayo is home to a wide diversity of tree and shrub species with forage potential, suggesting a potential for their use in agroforestry.

Keywords: animal nutrition; climate change; silvopastoralism; socio-ecosystems; sustainable livestock; traditional knowledge

RESUMEN

La ganadería en la región andino-amazónica colombiana se caracteriza por su baja competitividad y su impacto socioambiental negativo, siendo un factor de deforestación a nivel nacional y contribuyendo a la generación de gases de efecto invernadero. Los sistemas silvopastoriles (SPS) son una estrategia para reducir este impacto. Esta investigación se realizó con el objetivo de identificar y realizar la caracterización nutricional de especies arbóreas y arbustivas relevantes para SPS en la región andino-amazónica del Alto Putumayo. Se realizó un diagnóstico a través de encuestas semiestructuradas, visitas de campo y sesiones de diálogo de conocimientos, reconociendo especies potenciales y sus usos. Para la caracterización nutricional del forraje, las muestras fueron analizadas en laboratorio mediante tecnología de espectroscopía de infrarrojo cercano-NIRS. Posteriormente se realizó un análisis estadístico mediante una técnica de aprendizaje automático no supervisado basado en análisis de componentes principales. El agrupamiento jerárquico con el método de Ward identificó 38 especies leñosas con diferentes hábitos de crecimiento (arbustos y árboles), distribuidas en 20 familias, principalmente Asteraceae, Fabaceae y Moraceae. Aproximadamente el 60% de las especies identificadas son relevantes en la nutrición animal. Las especies con mejor calidad nutricional fueron *Sapium stylare*, *Sambucus nigra* y *Tithonia diversifolia*. Asimismo, se determinaron cuatro grupos, donde los dos primeros grupos representan el 79,1% de la varianza. En conjunto, nuestros hallazgos indicaron que el Alto Putumayo alberga una amplia diversidad de especies de árboles y arbustos con potencial forrajero, lo que sugiere un potencial para su uso en agroforestería.

Palabras clave: cambio climático; conocimientos tradicionales; ganadería sostenible; nutrición animal; silvopastoreo; socioecosistemas

INTRODUCTION

The livestock sector is a cornerstone of the Colombian economy. According to the Departamento Administrativo Nacional de Estadística (DANE, 2024), the economic activity encompassing ‘agriculture, livestock, hunting, forestry, and fishing’ demonstrated robust growth in 2024, registering an 8.1% increase and contributing 0.8 percentage points to the national Gross Domestic Product (GDP). This sector emerged as the primary driver of the country’s economic expansion during that year.

Further underscoring its significance, the Federación Colombiana de Ganaderos (FEDEGÁN, 2024) highlighted in its most recent report that the livestock sector continues to play a crucial role in the national economy. In 2023, Colombia’s beef and offal exports totaled approximately 12,140 tons, generating substantial revenues of USD 56.506 million.

In the Colombian Amazon Piedmont, the livestock system stands as one of the primary economic activities. This region holds significant importance, ranking fifth in the national bovine inventory according to Enciso *et al.* (2018).

However, the current profitability and socio-environmental impact of this system are notably limited. Its low profitability often leads to the adoption of extensive livestock farming practices, which, in turn, contribute significantly to deforestation hotspots nationwide (Pardo *et al.*, 2020). Furthermore, a substantial portion of greenhouse gas (GHG) emissions is attributed to this sector. The 2015 United Nations Framework Convention on Climate Change emphasizes the critical need for greater efficiency within this productive system, despite the challenges in altering global dietary patterns. Such efficiency gains are vital for enhancing environmental performance, improving productivity, and ultimately fostering increased profitability, competitiveness, and sustainability in the livestock sector.

Silvopastoral systems (SPS) are a multifaceted strategy offering numerous social, economic, and environmental benefits. They play a crucial role in rehabilitating areas degraded by livestock farming and fostering the interconnection of livestock landscapes through the creation of biological corridors (Obando-Enriquez, Castro-Rincón *et al.*, 2023). Furthermore, the forage species integrated into SPS contribute to mitigating greenhouse gas emissions by reducing methanogenesis in livestock. These systems also ensure a consistent and diverse supply of nutritious forage (Cardona-Iglesias *et al.*, 2020; Lerma-Lasso *et al.*, 2023).

Incorporating tree species into silvopastoral systems (SPS) presents a productive and sustainable reconversion strategy (Cabrera-Núñez *et al.*, 2019). This integration aids in atmospheric nitrogen fixation and the recycling of nutrients from deeper soil layers (Obando-Enriquez, Hernandez-Oviedo *et al.*, 2023), thereby restoring the soil's biological, physical, and chemical attributes and enhancing flora and fauna diversity (Jiménez-Mariña *et al.*, 2022). In the Sibundoy Valley, the focus on a limited number of grass species for forage creates monocultures highly susceptible to pests and diseases, posing a significant risk during health emergencies. Promoting forage diversity through natural pastures and integrating forest species with high nutritional potential is crucial. This approach can substantially increase both the quantity and quality of milk production (Riascos *et al.*, 2020).

Despite the recognized benefits of silvopastoral systems, a significant knowledge gap persists regarding the diversity of tree and shrub species with forage potential in the Andean-Amazon region, specifically their nutritional value for cattle. This deficit underscores the urgent need for further research to identify, characterize, and evaluate native species from this biodiverse area. Such efforts are crucial for their subsequent domestication and successful integration into livestock systems via silvopastoral approaches. Therefore, the present study aimed to identify and nutritionally characterize relevant and potentially valuable tree and shrub species for silvopastoral systems in Alto Putumayo. This work seeks to strengthen regional knowledge on the sustainable use and management of these production systems, ultimately contributing to improved livestock productivity and ecological resilience in the region.

MATERIALS AND METHODS

Characterization of the studied area.

The Alto Putumayo region is situated in southwestern Colombia, within the Andean-Amazonian geographical zone. It is precisely located at approximately 1° 12′ 12″ North latitude and 76° 51′ 15″ West longitude. This region encompasses the municipalities of Santiago, Colón, Sibundoy, and San Francisco. For the purpose of this study's sampling, only the municipalities of Santiago, Colón, and Sibundoy were included (Figure 1).

According to the Holdridge life zone classification, the area is characterized as very humid low montane forest (bmh-MB) (Duarte-Goyes *et al.*, 2019). Climatologically, Alto Putumayo experiences an average annual precipitation of 1578 mm and a relative humidity ranging from 81% to 83%. The region receives an average of 669.9 hours of sunshine annually, with an average temperature of 15.6 °C. Altitudinally, the region spans elevations between 2012 and 2908 meters above sea level (Astaíza Martínez *et al.*, 2017; Duarte-Goyes *et al.*, 2019; Mavisoy *et al.*, 2007; Medina-Castellanos *et al.*, 2017).

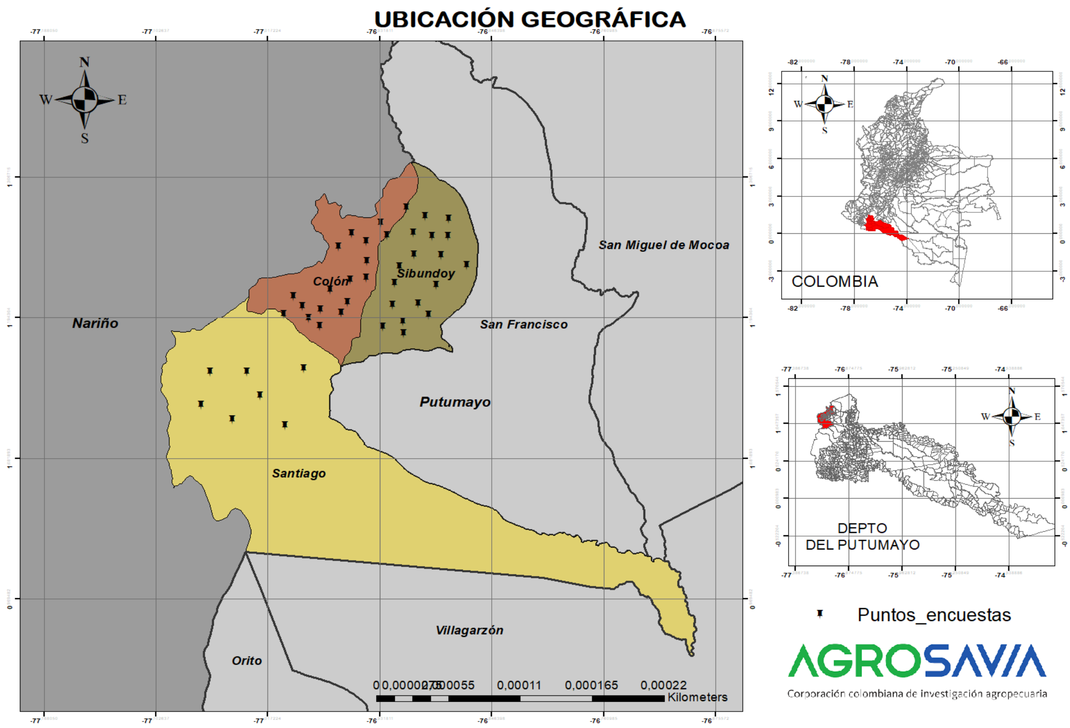

Figure 1. *Studied area.*

Species identification.

This process was conducted using semi-structured surveys that gathered data on 45 social, economic, and environmental variables. A total of 41 surveys were administered and supplemented through field trips and visits to leading producers. Subsequently, workshops were held as part of a "dialogue of knowledge" approach, where the most significant uses of both arboreal and shrub components were described and acknowledged. This collaborative effort facilitated the compilation of a list of common names, which were then cross-referenced with general and specific taxonomic literature for formal identification. Further support was provided by plant taxonomy specialists from the PSO herbarium at the University of Nariño (Colmenares-Arteaga *et al.*, 2013).

Nutritional characterization.

Sampling was carried out between August and November 2023. For each woody species, manual pruning was carried out at a height of 70 cm above ground level. The tender stems and leaves were collected and immediately weighed with a precision scale to determine the fresh biomass. Next, a 500 g subsample was taken as a forage sample and dried in an oven at 65 °C for 72 hours. This dried plant material was then sent to Agrosavia's specialised laboratories for analysis using near-infrared spectroscopy (NIRS). The NIRS analysis determined the concentrations of crude protein (CP), neutral detergent fibre (NDF), non-structural carbohydrates (NSC), net energy for lactation (NEL) and digestibility (DIG), following the methodology proposed by Guatusmal-Gelpud et al. (2020).

Multivariate statistical analysis.

The unsupervised machine learning technique of hierarchical clustering, based on Principal Component Analysis (PCA) as outlined by Kassambara

(2017), was conducted. This analysis was complemented by a cluster-type hierarchical grouping analysis employing Ward's method (Peña-Sánchez-de-Rivera, 2002). To implement these statistical methods, FactoClass (Pardo *et al.*, 2018), Factoextra (Kassambara & Mundt, 2020), FactoMiner (Husson *et al.*, 2022), and dplyr (Wickham et al., 2019) libraries within the R statistical software v.4.2.1® (R Core Team, 2022) were used.

Following these analyses, a participatory workshop was held with local livestock producers to disseminate the findings and gather valuable feedback regarding the analyses.

RESULTS

Species identification.

A total of 38 tree and shrub species, were identified from 20 distinct families. Among these, Asteracea (7.9%), Fabaceae (13.2%), and Moraceae (7,9%) were found to be the most prominent (see Table 1). Most families are represented by one species (2.6% and 5.3%), which may indicate high taxonomic diversity, but relative abundance concentrated in a few dominant families.

Table 1. *Identification and characterisation of tree and shrub species on livestock farms*

Species	Common Name	Family	Uses				
Trichanthera gigantea	Nacedero	Acanthaceae	Fje				
Saurauia scabrida	Moquillo	Actinidiaceae	Fr	Csr			
Baccharis latifolia (Ruiz & Pav.) Pers.	Chilca	Asteraceae	Lñ	Fje	Csr		
Smallanthus pyramidalis (Triana) H. Rob	Colla negra	Asteraceae	Fje	Lñ	Csr		
Tithonia diversifolia (Hemsl.) Gray	Botón de oro	Asteraceae	Fje	Orn			Csr
Alnus acuminata Kunth	Aliso	Betulaceae	Mdr	Fje	Csr		
Tecoma stans (L.) Kunth	Pichuelo	Bignoniaceae	Fje	Orn	Lñ	Smb	
Mimosa quitensis Kunth	Guarango	Caesalpiniaceae	Fje	Lñ			
Sambucus nigra L.	Sauco	Caprifoliaceae	Fje	Arts	Mdc	Csr	
Sambucus nigra subsp. peruviana (Kunth) bolli	Tilo	Caprifoliaceae	Fje	Arts	Mdc	Csr	
Carica fructifragrans H.	Chamburo	Caricaceae	Fr				
Weinmannia pubescens Kunth	Encino churoso	Cunoniaceae	Lñ	Csr			
Macleania rupestris	Chaquilulo	Ericaceae	Fr	Lñ	Csr		
Thibaudia floribunda	Uva de monte	Ericaceae	Fr	Csr			
Escallonia paniculata (Ruiz & Pav.) Schult.	Chilco colorado	Escalloniaceae	Lñ	Orn			
Acacia decurrens	Acacia amarilla	Fabaceae	Fje	Lñ	Smb		
Acacia melanoxylon	Acacia negra	Fabaceae	Fje	Lñ	Mdr		
Erythrina fusca Lour.	Pizamo, Cachimbo	Fabaceae	Fje	Mdr	Lñ		
Erythrina edulis	Chachafruto	Fabaceae	Fje	Fr	Csr		
Campsiandra comosa. Benth	Guamo, Chigo	Fabaceae	Fr				
Quercus humboldtii Bonpl.	Roble andino	Fagaceae	Mdr				
Juglans neotropica	Nogal	Juglandaceae	Fr	Mdr	Lñ		

Species	Common Name	Family	Uses			
Hibiscus rosa-sinensis	Resucitado	Malvaceae	Fje	Orn		
Tibouchina lepidota (Bonpl.) Baill.	Flor de mayo	Melastomata-ceae	Orn	Csr		
Cedrela montana Moritz ex Turcz	Cedro de montaña	Meliaceae	Mdr			
Morus nigra L	Morera	Moraceae	Fje			
Ficus Andicola Standl.	Caucho sabanero	Moraceae	Orn	Fr		
Ficus Gigantosyce. Dugan	Higuerón	Moraceae	Mdr			
Morella pubescens	Laurel de cera	Myricaceae	Csr	Cm		
Fraxinus chinensis	Urapán	Oleaceae	Smb	Mdr		
Pinus patula	Pino	Pinaceae	Mdr	Lñ		
Prunus serótina	Capulíx	Rosaceae	Fje	Fr		
Hesperomeles ferrugínea. Benth	Cerote	Rosaceae	Fr	Lñ	Mdc	
Salix babylonica L.	Sauce llorón	Salicaceae	Fje	Arts	Csr	Mdr
Pouteria lucuma (R.&P) Ktze.	Maco	Sapotaceae	Fr	Lñ	Mdc	
Cestrum petiolare Kunth	Tinto	Solanaceae	Orn			
Bohemeria nivea (L) Gaud	Ramio	Urticaceae	Fje			

Nomenclature: Handicrafts (HdC), Conservation (Csr), Cosmetics (Cm), Forage (Fge), Fruits (Fr), Firewood (Fw), Timber (Tb), Medicinal (Mdc), Ornamental (Orn), Shade (Sd).

With regard to the usual use of the tree and shrub species evaluated in this research, (see Figure 2) shows that the highest values are concentrated in forage use (60%), conservation (36%) and firewood (35.7%), while the lowest values are concentrated in ornamental (7%), medicinal (7%) and cosmetic (3.6%) uses.

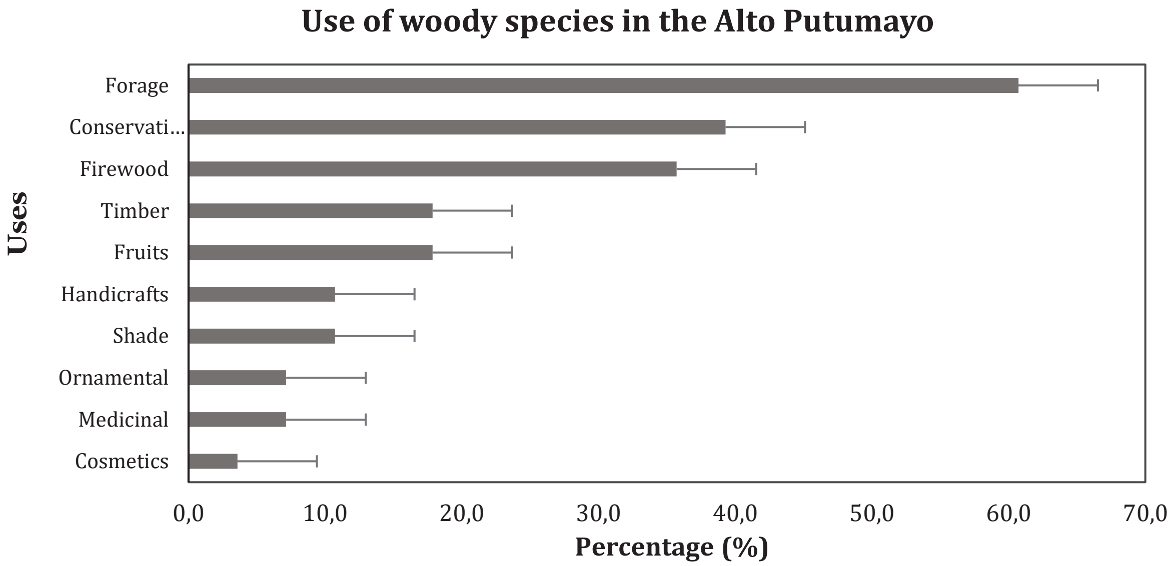

Figure 2. *Percentage of habitual use of woody species in the Alto Putumayo region.*

Evaluation of the nutritional composition of forage tree and shrub species.

On the other hand, Principal Component Analysis (PCA) conducted on the tree and shrub species data (Figure 3) revealed that the first two components collectively explain 79.10% of the total variance. Specifically, the first principal component accounts for 59.30% of the total variance, while the second component explains 19.80%. Analysis of the variable contributions to the first component indicated that Net Energy of Lactation (NEL) (13.95%), Total Digestible Nutrients (TDN) (13.92%), Digestibility (13.92%), Crude Protein (11.80%), and Phosphorus (11.73%) were the most influential. For the second component, the most significant variables were Calcium (34.36%), Acid Detergent Fiber (12.11%), Saponins (11.14%), and Neutral Detergent Fiber (7.42%).

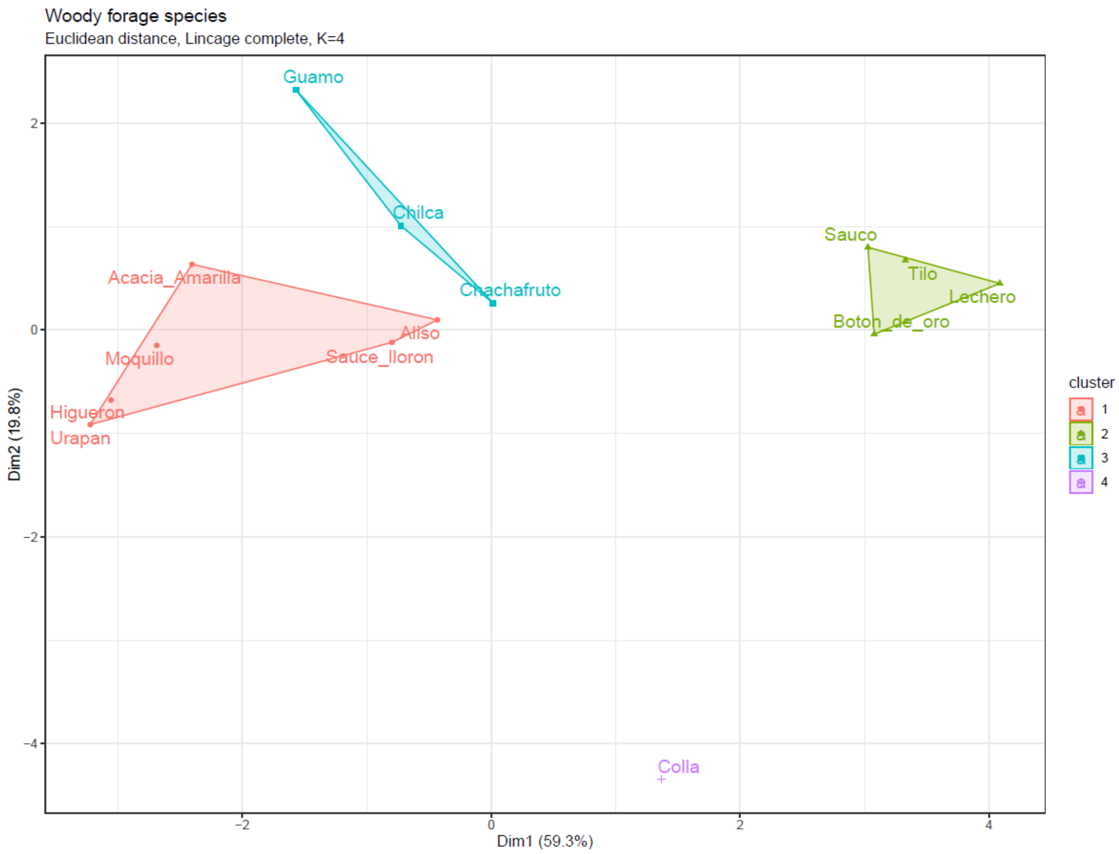

Figure 3. *Principal component analysis for tree and shrub species*

Cluster determination by hierarchical grouping in principal components (HCPC).

Four distinct clusters were identified (Table 2). Cluster I comprised 42.9% of the cases (six species), Cluster II encompassed 28.6% (four species), Cluster III included 21.4% (three species), and Cluster IV represented 7.1% (one species).

Following cluster identification, each woody forage species was spatially represented on the factor map (Figure 3). To validate the statistical model's classification and ascertain the relevance of the four identified clusters, a participatory workshop was conducted with dairy producers from the region. The workshop methodology involved the presentation of preliminary results using visual aids, followed by group discussions aimed at evaluating the forage utility of each species based on local empirical knowledge. A final plenary session then facilitated a collective assessment of the classification's relevance. This integrated approach allowed for a direct comparison between the statistically derived results and the producers' practical experience, thereby significantly enhancing the validity and robustness of the analysis.

Table 2. *Group formation through hierarchical clustering in principal components*

Group	Amount of species	%
I	6	42.9
II	4	28.6
III	3	21.4
IV	1	7.1

Based on Table 2 and Figure 3, the species were grouped according to their degree of similarity between the variables evaluated; therefore, **Group I** consisted of Acacia amarrilla (*Acacia decurrens*), Sauce (*Salix babylonica*), Aliso (*Alnus acuminata Kunth*), Moquillo (Saurauia aromatica), Higerón (Ficus americana), and Urapán (*Fraxinus chinensis*). **Group II** consisted of Sauco (*Sambucus nigra*), Botón de oro (*Tithonia diversifolia*), Lechero (*Sapium stylare*), and Tilo (*Sambucus nigra subsp. Peruviana*). **Group III** included Chachafruto (*Erythrina edulis*), Chilca (*Baccharis latifolia*), and Guamo (*Campsiandra comosa*), while Colla *(Smallanthus pyramidalis)* was placed in **Group IV**, given its degree of difference from the other species.

The following table (Table 3) shows the average nutritional composition (± standard deviation) of 17 tree and shrub species classified by functional groups (which arise from the principal component analysis performed previously). Key parameters for animal feed are included, such as DM (%): Dry matter, reflecting moisture content and nutrient concentration. CP (%): Crude protein, an indicator of the protein quality of the forage. EE (%): Ether extract, associated with fat and oil content. NDF and ADF (%): Neutral detergent fibre and acid detergent fibre, related to digestibility. TC (%): Condensed tannins, secondary metabolites that can affect consumption and digestibility. Saponins (%): Bioactive compounds with anti-nutritional and medicinal effects. NSC (%): Non-structural carbohydrates, a source of readily available energy.

Table 3. *Nutritional composition of forage tree and shrub species*

Scientific name	Group	DM (%)	σ	CP (%)	σ	EE (%)	σ	NDF (%)	σ	ADF (%)	Σ	TC (%)	σ	Saponinas (%)	σ	NSC (%)	σ
Alnus acuminata	I	18.3	2.2	18.1	4.13	3.03	0.4	46.52	6.3	19.23	3.6	8.85	3.96	22.72	3.75	13.17	4.4
Baccharis latifolia	III	21.5	2.6	20.1	3.05	3.24	0.5	45.41	3.1	27.14	2.7	6.9	4.04	22.15	6.76	7.22	3
Boehmeria nivea	-	19.8	0.5	21.9	1.4	2.19	0.8	41.41	2.3	20.49	2.1	0.81	2.3	15.26	2.6	10.79	1.3
Erythrina edulis	III	20.2	2.5	21.5	3.45	2.15	0.8	50.01	5.8	28.07	1.6	2.07	1.9	12.81	2.43	6.74	0.8
Ficus americana	I	21.2	0.1	14	0.07	1.72	0.3	55.43	2.7	23.16	0.8	10.8	0.49	28.55	6.12	14.74	0.7
Fraxinus uhdei	I	21.6	4.7	12.9	2.64	1.7	0.3	51.28	5	24.47	1.5	5.51	3.35	24.44	2.18	13.92	1.6
Inga ornata	III	17.4	0.6	21.1	2.34	1.47	0.3	51.32	5.1	28.61	2.9	9.02	2.19	22.59	2.55	8.44	1.6
Morella pubescens	-	16.9	0.1	14.1	1.19	3.03	0.6	40.51	2.7	24.25	0.5	21.3	0.4	39.83	8.63	17.56	1.3
Myrcianthes leucoxyla	-	12.9	0.5	14.8	14	2.11	0.5	38.34	3.2	19.97	0.9	9.43	13.3	29.93	22.4	16.01	6.3
Salix babylonica	I	20.4	4.5	18.9	2.66	2.07	0.8	41.46	4.3	23.17	1.3	10.4	2.35	26.01	3.34	12.16	1.7
Sambucus nigra	II	18.4	3.9	24.8	1.43	3.17	0.3	39.62	2.4	20.77	0.9	3.5	0.8	20.36	3.67	13.1	1.9
Sambucus peruviana	II	19.4	0.2	25	4.33	2.6	0.7	37.3	5.9	19.39	1	2.8	3.95	16.24	11	13.49	1.6
Sapium stylare	II	25.7	2.1	26	2.9	3.34	0.4	38.47	3.2	20.65	0.6	1.61	1.4	16.83	3.1	13.08	2.5
Saurauia aromatica	I	19.7	1.7	15.4	2.33	1.71	0.5	50.72	3.3	24.32	1.5	10.3	4.38	26.58	6.67	13.82	2.1
Senna siamea	I	15.2	0.2	17.6	0.36	3.97	0.5	48.4	4	24.55	0.5	14.4	0.35	35.39	2.31	12.58	0.3
Smallanthus pyramidalis	IV	20.6	4	16.5	1.68	2.02	0.2	29.97	3.5	18.78	2.1	2.41	1.59	5.1	3.16	16.17	2.3
Tithonia diversifolia	II	17.5	2.9	24.5	5.78	1.73	0.3	43.25	4.5	21.78	2.2	1.68	1.94	18.41	2.96	10.55	3

DM: Total Dry Matter, CP: Crude Protein, EE: Ethereal Extract, NDF: Neutral Detergent Fiber, $\bar{x}$ of FDA: Acid Detergent Fiber, TC: Condensed Tannins, Saponins , NSC: Non Structural Carbohydrates

DISCUSSION

Identification and characterisation of tree and shrub species on livestock farms.

In the identification and characterisation of shrub and tree species, the results of this research coincided with those reported by Jiménez Mariña et al. (2022), who also highlighted the relevance of the Fabaceae family in the province of Granma, Cuba, with a representation of 18%. Similarly, Narváez Herrera et al. (2023) identified the Fabaceae, Asteraceae and Sterculiaceae families as particularly important in the Amazonian Piedmont, attributing their relevance to their role as an essential source of food for animals in times of scarcity, as well as their remarkable adaptability to develop and survive in natural conditions. Likewise, Juárez García and Saragos Méndez (2019) highlighted the value of these species due to the high protein content present in their leaves and young stems.

With regard to the classification of species according to their use, it should be mentioned that many of the species identified in this research are important because they offer various ecosystem benefits. For example, elderberry (Sambucus nigra L.), chachafruto (Erythrina edulis), pichuelo (Tecoma stans (L.) Kunth), black wattle (Acacia melanoxylon), yellow wattle (Acacia decurrens) and weeping willow (Salix babylonica L.) provide services such as fodder, soil conservation, shade for livestock, firewood, rehabilitation of degraded systems, nutrient input to the soil through nitrogen fixation, and biodiversity conservation (Bacca et al., 2023; Lerma-Lasso et al., 2023; Urbano Estrada et al., 2020).

This versatility underscores the critical importance of trees and strongly supports the integration of a tree component into livestock production systems through silvopastoral systems (SPS), especially in areas where monoculture pastures, common in the region, prevail (Obando-Enriquez, Bacca-Acosta *et al.*, 2023). In addition, the high rainfall and humidity characteristic of the Amazonian Piedmont create favourable conditions for the rapid development of tree species as a viable alternative forage in livestock systems, as pointed out by Pardo et al. (2020).

Figure 2 shows the distribution of the different uses of the identified species, highlighting their high potential for ecological restoration processes. Of the total recorded, 60% is used as fodder and 36% has value for conservation purposes, which is particularly relevant for the recovery of areas degraded by anthropogenic activities such as extensive agriculture and livestock farming. Beyond these uses, 21% of the species are used for firewood production and 18% provide wood and fruit. In this regard, Bacca Acosta and Burbano (2018) point out that agricultural and livestock practices are some of the most frequent disturbances in the Andean region. Guarnizo et al. (2020) highlight that livestock farming in the department of Putumayo has significantly altered the land cover (15.9% deforestation) through logging and burning, resulting in an estimated loss of 138,176 hectares between 2017 and 2018. Therefore, the incorporation of the tree and shrub species identified in this assessment represents an effective strategy for the productive conversion of degraded systems, while contributing to the conservation of local biodiversity.

Similarly, Lerma Lasso *et al.* (2023) indicate that the woody component within silvopastoral systems presents a promising and successful option for the restoration of landscapes degraded by conventional livestock systems. Concurrently, Cabrera-Núñez *et al.* (2019) establish that incorporating shrub and arboreal plants into pastures significantly contributes to reducing deforestation and soil degradation, both activities that have unfortunately escalated in recent years, leading to a decline in local biodiversity.

These results indicate that the participating community acknowledges the importance of tree and shrub species for forage production. However, scientific literature lacks comprehensive studies detailing the implementation and evaluation of silvopastoral systems (SPS) within the region (Narváez-Herrera *et al.*, 2023). This limited documentation may stem from insufficient incentives in public policies or inadequate support for initiatives promoting the adoption of alternative production systems like SPS.

Furthermore, the scientific review conducted establishes that the species identified in this study also demonstrate significant relevance in the medicinal and pharmaceutical fields, as highlighted by several studies. For example, Sharifee et al. (2024) reported that Morus nigra L. has antimicrobial and immunomodulatory properties that actively promote wound healing. Similarly, Valarezo et al. (2023) discovered that Morella pubescens contains sesquiterpene hydrocarbons, including (E)-caryophyllene and limonene, which exhibit potent antioxidant and antibacterial activities. In addition, secoiridoid glycosides extracted from the stem bark of Fraxinus chinensis Roxb. are commercially used in health products in many countries to improve intestinal function and control gouty arthritis, as documented by Chang et al. (2020).

In the realm of environmental remediation, *Salix babylonica* L. shows promise for phytoremediation of contaminated wastewater, with its cuttings effectively removing aniline, a common pollutant from pesticides (Li *et al.*, 2021). More recently, Tran *et al.* (2024) indicated that *Boehmeria nivea* contains vital compounds like 4-hydroxybenzoic acid and ursolic acid, these can serve as biological insecticides to control Aedes and Culex mosquito larvae, which are crucial vectors for diseases such as dengue, Zika, yellow fever, and chikungunya. Lastly, the genus *Erythrina* is known for producing flavonoids with promising antioxidant activity, offering a potential natural alternative for treating inflammatory pain (Jiménez-Cabrera *et al.*, 2021).

Nutritional composition of forage tree and shrub species.

Table 3 clearly demonstrates the significant nutritional value of *Tithonia diversifolia, Sambucus nigra, Sambucus peruviana, Sapium stylare, Erythrina edulis*, and *Inga ornata*, underscoring their potential as animal feed. These species are particularly noteworthy for their high crude protein content, low tannin levels, and favorable profiles of beneficial secondary compounds. Specifically, *S. stylare* and *T. diversifolia* are exceptional due to their high protein content (>24%) and low tannin content (<2 g/kg DM). This combination significantly enhances both palatability and digestibility for livestock. *S. peruviana* and *S. nigra* offer a strong protein profile coupled with intermediate levels of saponins, which can promote rumen health without negatively impacting digestion. While *E. edulis* and *I. ornata* have slightly higher fiber content, they still provide valuable protein and secondary metabolites that could offer physiological benefits to animals.

The dry matter (DM) content of *T. diversifolia* recorded in this study was 17.5%. This value is higher than the 15.3% reported by Uu-Espens *et al.* (2023) but lower than the 19% observed by Argüello Rangel *et al.* (2020) across different precipitation periods. Notably, Paniagua Hernández *et al.* (2020) reported significantly higher DM values for *T. diversifolia*, ranging from 71.6% to 85.2%, while Quiñones Chillambo *et al.* (2020) found a DM content of 20.5%. This considerable variation in reported DM values for T. diversifolia can be attributed to environmental conditions at the time of sampling, particularly in regions with bimodal climates, as highlighted by López Vigoa *et al.* (2019). Such variability in DM availability underscores the importance of integrating herbaceous and woody components in livestock production systems. This approach, which aims to improve nutritional balance, increase year-round green forage availability, and enhance productive stability, is crucial for mitigating forage seasonality and intensifying livestock reconversion efforts.

The analysis of *T. diversifolia* revealed a crude protein (CP) content of 24%, acid detergent fiber (ADF) of 21%, and neutral detergent fiber (NDF) of 43%. These values demonstrate variations when compared to previously published literature. For instance, Alonso-Vásquez *et al.* (2021) reported a broader range for *T. diversifolia* CP, between 14.0% and 36.6%, with NDF values around 35.5% and ADF at 30.4%. Similarly, Paniagua-Hernández *et al.* (2020) documented CP values ranging from 8.9% to 17.5%, and NDF between 32.7% and 42.5%. Quiñones Chillambo *et al.* (2020) obtained comparable values of 22.4% for CP, 35.3% for NDF, and 30.4% for ADF.

The observed discrepancies in CP content can be attributed to a confluence of factors, including the plant's phenological stage at the time of sampling, the specific agro-ecological conditions (e.g., soil characteristics, climatic variations, altitude), and the management and fertilization practices employed (Navas-Panadero *et al.*, 2021). Of particular relevance is the considerably lower ADF value (21%) compared to those reported by Alonso-Vásquez *et al.* (2021) and Quiñones Chillambo *et al.* (2020). A lower ADF content typically signifies enhanced digestibility of the fibrous fraction, which is highly advantageous for animal nutrition. Conversely, our NDF value (43%) is slightly higher than some reported values, which may indicate a greater proportion of structural carbohydrates (cellulose and hemicellulose) within the plant material, potentially influencing its overall digestibility (Navas-Panadero *et al.*, 2021).

The dry matter (DM) content of *Sambucus nigra* was determined to be 18.4%. This finding is consistent with several other studies conducted in the region. Navas Panadero et al. (2021) reported a DM content of 19.7%, while Guatusmal-Gelpud et al. (2020) and Cardona-Iglesias et al. (2020) both indicated values of 19% and 19.7%, respectively. Gálvez Cerón and Erazo Gómez (2019) observed a higher DM value of 33.12% for the interaction between *Acacia decurrens* and *Sambucus nigra* within silvopastoral systems in Nariño, although this figure pertains to a specific intercropping arrangement rather than *S. nigra* as a standalone species. Beyond its comparable DM content, *S. nigra* is recognized for its palatability and balanced nutritional profile, as highlighted by Osorio-Molina et al. (2022). These attributes collectively position *Sambucus nigra* as a viable and valuable option for diversifying the diet of ruminants, particularly in high Andean environments.

This research found the nutritional composition of *Sambucus nigra* to be 24.8% crude protein (CP), 39.62% neutral detergent fiber (NDF), and 20.77% acid detergent fiber (ADF). These results are largely consistent with other studies. For instance, Navas Panadero *et al.* (2021) reported similar values for *S. nigra*: 23.7% CP, 35.6% NDF, and 18.7% ADF, indicating a general agreement in the overall nutritional profile. However, some variations exist. Cardona-Iglesias et al. (2020) reported slightly lower values, with 22.1% CP, 36.4% NDF, and 14.8% ADF. Such differences can be attributed to several factors, including variations in agro-ecological conditions, the phenological stage of the plant at the time of sampling, or discrepancies in the analytical methodologies employed.

Guatusmal-Gelpud et al. (2020) reported a crude protein (CP) content of 26.5% for Sambucus nigra, which is higher than the findings in the current study. However, their reported neutral detergent fiber (NDF) of 28.86% and acid detergent fiber (ADF) of 14.06% were considerably lower. These lower fiber values would suggest a reduced proportion of structural fiber components and, consequently, potentially higher forage digestibility. This observed variability among studies underscores the significant influence of various factors on the chemical composition of plant material, including soil type, altitude, agronomic management practices, and harvest time.

Sapium stylare presents a highly favorable nutritional profile for ruminant forage. Its crude protein content is notably high at 26%. The dry matter percentage of 25.7% suggests good stability, which is beneficial for preservation methods like silage. Furthermore, its relatively low neutral detergent fiber (38.47%) and acid detergent fiber (20.65%) values, especially when compared to other tree species, indicate a potentially high digestibility for livestock.

Sapium stylare boasts an ether extract (lipid) content of 3.34%, which is higher than the average observed in the other shrub forages evaluated. This elevated lipid content provides an additional energy source for ruminants. The species also contains a low concentration of condensed tannins (1.61%), minimizing the risk of adverse anti-nutritional effects on protein digestibility. While a moderate level of saponins (16.83%) is present, which could offer benefits such as a reduction in parasite load, it's worth noting that excessively high concentrations might negatively impact palatability. Furthermore, the non-structural carbohydrate content of 13.08% suggests a readily available source of fermentable energy, contributing to a favorable rumen balance.

The nutritional analysis revealed a crude protein (CP) content of 21.49%, neutral detergent fiber (NDF) at 50%, and acid detergent fiber (ADF) at 28%. These findings align with previous research; for instance, Delgado-Soriano *et al*. (2020) reported comparable CP levels of 21%. Similarly, Choque Durand *et al*. (2018) and Cárdenas Villanueva *et al*. (2016) observed CP ranges between 20.1% and 23.5%, ether extract between 0.4% and 2.5%, and ash content between 8.6% and 11.6%. In contrast, Cárdenas Villanueva *et al*. (2021) reported higher average NDF values of 58% and ADF between 32.6% and 34.7% compared to those found in this study. It is important to note that forages with NDF levels below 50% are generally preferred in animal feed due to their enhanced digestibility and energy intake (Cardona-Iglesias *et al*., 2020). Therefore, the nutritional profile of *E. edulis*, particularly its high protein content and moderate structural fiber levels, suggests it is an adequate and promising alternative for use in sustainable animal feeding systems.

The nutritional characterization of Inga *ornata* revealed a crude protein content of 21.1%, indicating its relevance as a protein source for livestock diets. However, the low dry matter content (17.4%) suggests a high moisture content, which could limit its preservation in fresh or ensiled forms. High levels of neutral detergent fiber (51.32%) and acid detergent fiber (28.61%) were observed, potentially negatively impacting digestibility and voluntary intake. The ether extract content was low (1.47%), which is consistent with the typical profile of tropical forages.

Analysis also identified high concentrations of condensed tannins (9.02%) and saponins (22.59%). While these compounds can offer benefits such as improved protein efficiency and anti-parasitic effects, their high levels could negatively impact palatability and digestive efficiency if not managed appropriately. The non-structural carbohydrate content (8.44%) suggests a moderate source of rapidly fermentable energy. These findings collectively position *Inga ornata* as a high-protein complementary forage source. Its strategic inclusion, when combined with other forage species, holds the potential to optimize nutritional efficiency within animal production systems.

For *Smallanthus pyramidalis*, the nutritional results were comparatively less favorable than other species, exhibiting crude protein (CP) at 16.5%, acid detergent fiber (ADF) at 19%, and neutral detergent fiber (NDF) at 30%. This may be attributable to the specific ripening period or the cutting height employed during sampling. However, *Smallanthus pyramidalis* remains a promising species due to its rapid development, consistent availability of green forage, excellent adaptability, and its capacity to provide multiple ecosystem services, including the production of flours suitable for animal feed.

In the present study, this species is distinguished from others in the territory by its high calcium content (2.03%). Furthermore, it exhibits low values for tannins (16.92%), saponins (5.10%), neutral detergent fiber (NDF) (29.97%), and acid detergent fiber (ADF) (18.78%). These values differ from those reported by Cardona Iglesias et al. (2022), who observed 13.55%, 13.89%, 34.6%, and 12.2% for these respective parameters after 70 days.

The comparative nutritional analysis among five forage species—*Tithonia diversifolia*, *Sambucus nigra, Sapium stylare, Erythrina edulis*, and *Inga ornata*—revealed significant differences in their bromatological composition. *Sapium stylare* exhibited the most balanced nutritional profile, characterized by high dry matter (25.7%), crude protein (26%), and ether extract (3.34%). These were accompanied by low levels of neutral detergent fiber (38.47%) and acid detergent fiber (20.65%), suggesting high digestibility. Furthermore, *Sapium stylare* showed moderate concentrations of condensed tannins (1.61%) and saponins (16.83%), with an adequate energy content reflected in its proportion of non-structural carbohydrates (13.08%).

Similarly, *Sambucus nigra* also exhibits high nutritional value, presenting high levels of crude protein (24.8%) and energy (ether extract [EE]: 3.17%; non-structural carbohydrates [NSC]: 13.1%). However, it is associated with higher concentrations of anti-nutritional compounds. In contrast, *Inga ornata* and *Erythrina edulis* demonstrated elevated levels of fiber (neutral detergent fiber [NDF] > 50%) and saponins (>12%), which could limit their primary use as forage. These findings suggest *Sapium stylare* and *Sambucus nigra* are the most promising options for animal production systems focused on improving diet quality and feed efficiency, given proper management of their secondary metabolites

CONCLUSIONS

In collaboration with local producers, 38 shrub and tree species with multiple uses were identified, including fodder supply and conservation functions. This finding is significant, as these species represent a strategic alternative for the implementation of silvopastoral systems (SPS) in areas degraded by conventional livestock farming in the region, contributing to the productive and ecological recovery of these environments.

Of the 20 taxonomic families identified, 60% of the species are relevant for animal nutrition, with Sapium stylare, Sambucus nigra and Tithonia diversifolia being particularly noteworthy. These findings establish Alto Putumayo as a niche that is home to a wide diversity of tree species with forage potential, representing a favourable scenario for the implementation of silvopastoral or other agroforestry systems.

Based on the productive dynamics of the region, future research should conduct nutritional analyses of these species at different stages of growth (ages), cutting heights and throughout the different seasons of the year. These comprehensive analyses would facilitate the development of technical recommendations for optimal management and adequate synchronisation of forage supply, thus maximising the nutritional intake for cattle and other smaller livestock species, such as guinea pigs.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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