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Assessment of soil characteristics and the productive potential of native Poaceae forage species in the central highlands of Peru

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ABSTRACT

Given the increasing pressure on natural grassland ecosystems in the Peruvian high Andes, optimizing the use of native forage species has become essential for understanding the relationship between soil characteristics and the productive potential of these plants. This study evaluated the relationship between soil properties and the productive potential of three native forage species: *Festuca dolichophylla, Cinnagrostis vicunarum*, and *Jarava ichu*. The research was conducted in natural grasslands in the district of Yauli, province of Yauli, department of Junin, at approximately 4000 m.a.s.l. During the dry season 2023, soil samples were collected following standardized protocols, and key soil parameters were analyzed. The nutritional characteristics of the forage species were also assessed, including dry matter content, total protein, calcium, phosphorus, in vitro organic matter digestibility, and metabolizable energy. The results revealed significant differences among species. *Festuca dolichophylla* exhibited the highest protein content (10.7%), superior digestibility (52.5%), and greater metabolizable energy (8.4 MJ·kg^{-1}), making it the most suitable forage option for livestock in the highland ecosystem over 4000 m.a.s.l., where environmental factors constrain agricultural activity. In contrast, *Cinnagrostis vicunarum* and *Jarava ichu* showed lower protein levels, with *Jarava ichu* displaying particularly low digestibility (28.9%) and energy content (4.6 MJ·kg^{-1}), limiting its productive potential despite its high dry matter yield. These findings provide a strong scientific foundation for developing sustainable grassland management strategies in the Peruvian Andes, supporting the implementation of agronomic practices that enhance forage productivity while contributing to biodiversity conservation. Moreover, this study highlights the importance of soil characterization as a key tool for optimizing forage resource utilization in high-altitude farming systems, facilitating informed decision-making in land management and environmental remediation policies.

Keywords: native grasses, soils, Poaceae, highland grasslands, nutritional quality.

INTRODUCTION

Grasslands are among the largest ecosystems globally, covering approximately 20% of the Earth's land Surface (Zhou et al., 2020). In Peru, natural grasslands dominate the non-agricultural landscape, extending across approximately 18.1 million hectares, which accounts for 57% of the national territory (INEI, 2013). These ecosystems support a diverse megavascular flora, with key plant families including Poaceae, Rosaceae, Asteraceae, Plantaginaceae, Fabaceae, and Cyperaceae. Many of these species play a crucial role in Andean livestock feeding (Yaranga Cano et al., 2024), serving as forage for domestic animals such as sheep, cattle, and camelids during grazing periods (Grünwaldt et al., 2016; Yaranga Cano et al., 2024). The productivity and performance of grazing livestock depend on the palatability, availability, and nutritional quality of forage species (Abdullah et al., 2017). Therefore, the sustainable management of rangelands is essential for ensuring successful livestock production while maintaining ecosystem health.

The origins of the Poaceae family, also known as grasses, date back approximately

80–100 million years. Today, it comprises around 12,000 species classified into 771 genera and 12 subfamilies (*Anomochlooideae*, *Aristidoideae*, *Arundinoideae*, *Bambusoideae*, *Chloridoideae*, *Danthonioideae*, *Micraioideae*, *Oryzoideae*, *Panicoideae*, *Pharoideae*, *Puelioideae*, and *Pooideae*) as stated by Soreng et al. (2015). These species include annuals, biennials, and perennials, characterized by hollow stems and leaves that grow from the plant's base (García-Mozo, 2017). Poaceae are primarily wind-pollinated, with most species possessing pendulous anthers that produce large quantities of uniform pollen dispersed into the atmosphere (Erdtman, 1986; García-Mozo, 2017). Soreng et al. (2022) provided an updated global phylogenetic classification of Poaceae, identifying 11,783 species distributed across 12 subfamilies, 7 supertribes, 54 tribes, 5 supersubtribes, 109 subtribes, and 789 accepted genera. In the Andean region of Peru, the predominant ecosystems are tussock grasslands and highland grasslands, which are classified based on desirable (D) and less desirable (LD) forage species. Key grass species in these ecosystems include *Cinnagrostis vicunarum*, *Jarava ichu*, *Bromus lanatus*, *Festuca dolichophylla*, *Aciachne pulvinata*, *Muhlenbergia peruviana*, *Calamagrostis tarmensis*, *Dissanthelium mathewsii*, and *Calamagrostis glacialis* (Ibarra, 2020; Arias Arredondo et al., 2024) which generally exhibit relatively low nutritional quality, with an average protein content of 7.7%, neutral detergent fiber (NDF) of 70.8%, and a limited metabolizable energy value of 5.2 MJ/kg dry matter—considered suboptimal for ruminant nutrition (Flores et al., 2009).

From an edaphic perspective, the soil is a non-renewable natural resource essential for human well-being and the biosphere. Its significance lies in its ability to provide critical ecosystem services that maintain terrestrial balance (Yu et al., 2018). Soil quality is determined by its physical, chemical, and biological components (Ghaemi et al., 2014), which enable it to function as a support medium for plants and microorganisms. As a living and dynamic system, soil is crucial in sustaining various land management practices. High Andean soils are characterized by an arable layer ranging from 10 to 30 cm. These soils are often acidic, rich in organic matter, and predominantly classified as sandy loam in texture (Arias Arredondo et al., 2024).

Overgrazing results from approximately 35% of the world's degraded grasslands (Zhou et al., 2020). In Peru, the Ministry of Environment (MINAM) reported in 2020 that more than 60% of high Andean grasslands are undergoing degradation. The primary causes include the absence of conservation policies, inadequate watershed management, overgrazing, land-use changes, overexploitation, and climate change. These factors contribute to the deterioration of this valuable resource, as evidenced by increased soil erosion, reduced vegetation coverage, and a decline in desirable or palatable native grasses (Vásquez et al., 2023; Tácuna et al., 2015). Overgrazing of natural grasslands leads to a decline in the richness of highly palatable and desirable plant species (Louhaichi et al., 2009) and the destruction of native forage plants, which are often replaced by annual species with low forage value or by unpalatable and toxic plants (Gondard et al., 2003; Belgacem and Louhaichi, 2013). Examples of such undesirable species in the Andean region include *Astragalus peruvianus*, *Lachemilla aphanoides*, and *Austrocylindropuntia floccosa* (Arias Arredondo et al., 2024). Furthermore, grassland degradation negatively impacts ecosystem functions, leading to soil fertility loss (Vásquez et al., 2023). Overgrazing physically disturbs the topsoil layer, reducing vegetation coverage and accelerating soil degradation through processes such as erosion, excessive leaching, compaction, acidification, decreased cation exchange capacity, and diminished microbial activity—ultimately impairing soil fertility (Chadaeva et al., 2021; Bogunovic et al., 2022; Mensah, 2015). Reduced infiltration capacity and soil moisture further degrade grassland conditions, decreasing livestock productivity and forage availability (Pyke et al., 2002).

Excluding livestock grazing to protect grasslands is widely regarded as a straightforward and effective strategy for restoring vegetation structure in degraded arid grasslands. This approach has been shown to increase the abundance of palatable plant species, such as *Bromus catharticus*, *Werneria nubigena*, *Poa candamoana*, *Trifolium amabile*, *Festuca dolichophylla*, *Calamagrostis vicunarum*, and others (Arias Arredondo et al., 2024; Belgacem et al., 2013). Effective topsoil layer management also contributes to recovery efforts by reducing nutrient losses and promoting soil fertility restoration. Revegetation is the most widely accepted and practical method for improving soil fertility in degraded lands. This process involves planting tillers of desirable species to enhance vegetation coverage, thereby controlling soil erosion (Mensah, 2015; Jia et al., 2023). Finally, land managers should consider adopting a passive restoration approach, emphasizing natural regeneration based on the ecosystem's inherent resilience (Holl and Aide, 2011).

Consequently, revegetation can increase the proportion of desirable species to over 50% compared to overgrazed áreas (Gamoun, 2014). In addition, it helps restore potential benefits related to native vegetation coverage, soil retention, carbon storage and sequestration, food provision, and other and other benefits (Lázaro-González et al., 2023). Tácuna et al., (2015) demonstrate that revegetation using natural cuttings and the application of organic matter enhances vegetation coverage, yield, and the nutritional quality of pastures, contributing to the sustainability of grassland ecosystems.

Other studies in highlands in other latitudes, as in the case of Armenia, reveal that grazing negatively affects plant biomass and diversity, as well as soil nitrogen content (Navasardyan et al., 2024), Studies in the German Alps showed low resistance of annual net primary production in intensively managed communities under dry conditions, in contrast to extensively managed communities (Berauer et al., 2021).

This study aimed to evaluate the relationship between edaphic characteristics and the productive potential of three native Poaceae forage species in different regions of the Peruvian highlands, intending to optimize the management and sustainable use of these forage resources in highland farming systems.

MATERIALS AND METHODS

Study area

The study area is located in the natural highland grasslands in the district of Yauli, Yauli province, in the department of Junin, at 4000 m a.s.l. in central Peru (11°37′ S, 76°1′ W) as shown in Figure 1. The site's climate is classified as tundra (ET) according to the Köppen-Geiger climate classification (Kottek et al., 2006), with a distinct rainy season from October to April and a dry season from May to September. Daily temperatures range from 0 °C to 10 °C, with nighttime temperatures dropping below 0 °C. Mean annual precipitation ranges from 622 to 703 mm, with approximately 80% of this rainfall occurring during the growing season from December to March (Giráldez et al., 2020). The dominant vegetation coverage consists of grassland, with communities of *Festucas, Jaravas,* and *Cinnagrostis* prevalent.

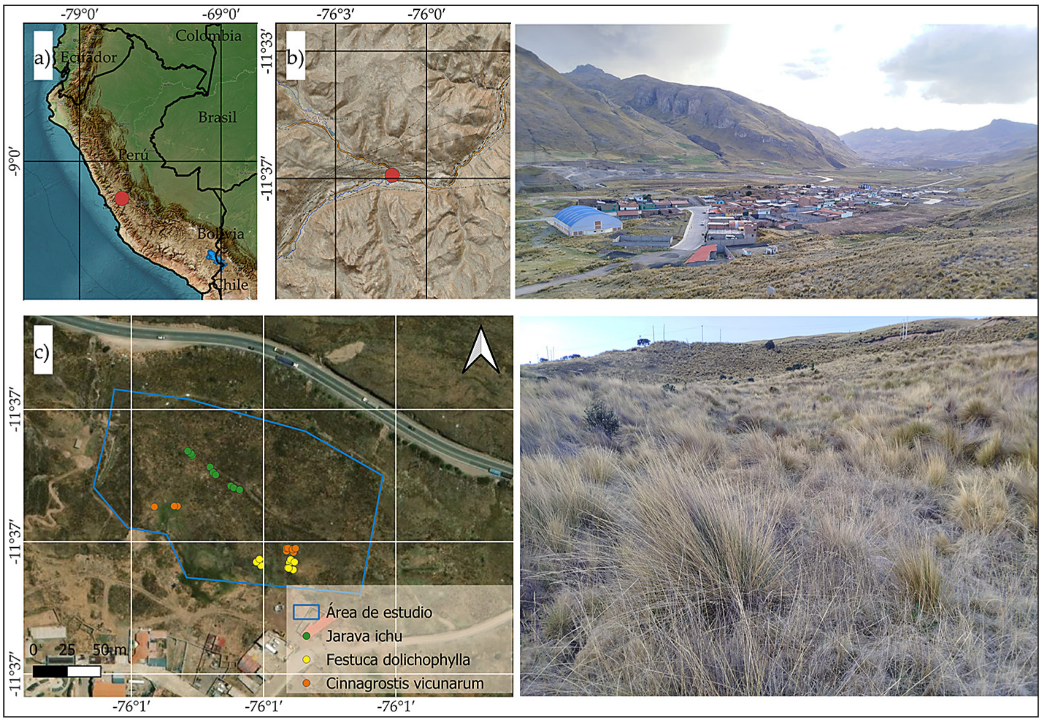

Figure 1. (a) Location map of the study site in Peru, (b) study site location in the central highlands of Peru with a panoramic view of the area, and (c) study area with sampling points of the evaluated Poaceae species and a view of the natural grassland with predominant pastures

Species collection

Three grass species, identified as the most common for grazing animals in the Yauli pastures, were evaluated. Sample collection was conducted at the beginning of the flowering stage during the dry season 2023. The three perennial species collected are grass species classified as desirable, undesirable, and undesirable for grazing (Table 1).

a) *Festuca dolichophylla* is a native, perennial grass that thrives at high elevations and is widely distributed across the Andes of South America. It is crucial in Andean ecosystems, primarily serving as a food source for South American camelids such as llamas and alpacas (Eduardo-Palomino et al., 2024). This species reproduces through both seeds and vegetative tillers and possesses physiological and ecological characteristics that enable it to withstand extreme environmental conditions, including temperature fluctuations, drought, and nutrient-poor soils (Eduardo-Palomino et al., 2024; Vila et al., 2022). It thrives in a range of soil types, from strongly acidic to slightly alkaline, with textures varying from loam, sandy clay loam, and clay loam to clay, all influenced by the cold, semi-arid Andean climate. Additionally, this species forms mycorrhizal associations, stores significant amounts of carbon fixed in its stems, and can bioaccumulate mercury, lead, and arsenic (Eduardo-Palomino et al., 2024).

b) *Cinnagrostis vicunarum* is distributed throughout South America, extending into Central America (Tovar Serpa, 1993). It is a perennial, spiny, or rhizomatous plant characterized by a hard, distinctly sulcate caryopsis with a hilum measuring 1/6 to 1/3 of the grain length. Its lemma horns are straight or slightly curved, clearly distinguishable from the callus hairs, and inserted from near the base to the middle, without slightly exceeding the lemma apex. The callus hairs measure 0.1–3 mm, covering 1/10 to 3/4 of the lemma length. The rachilla may be glabrous or sparsely to densely hairy, with hairs not reaching the lemma apex. The species features contracted panicles with one or three anthers and entire lanceolate lodicules (Peterson et al., 2019). It grows in rocky, wet, and dry soils and is well adapted to extreme altitudinal conditions and various soil types.

c) *Jarava ichu* is native to the Andes of Peru, Chile, Bolivia, and Argentina. This variety differs from var. ichu for including plants ranging from 0.10 to 1.20 m in height, with a ligule featuring a fringed margin, inflorescences measuring 5–15 cm, and spikelets with awns of 2–3 mm in length (Cialdella, 2010). These plants form extensive grasslands and are a characteristic component of the highland ecosystem. *J. ichu* is the most widely distributed species in the Andes (Tovar Serpa, 1993), thriving in acidic and dry soils.

Soil analysis – edaphic characteristics

Soil samples from the species under study were collected simultaneously with the plant sampling. Physicochemical analyses were conducted at the Soil, Water, and Foliar Laboratory (LABSAF) of the Santa Ana Experimental Station. Soil parameters were analyzed according to standardized methods: pH was determined using 9045D method (USEPA, 2004), electrical conductivity ($mS \cdot m^{-1}$) was measured following ISO 11265 (ISO, 1994), organic matter (%) was quantified using the AS-07 method of Walkley and Black, nitrogen (%) through AS-08 method using the micro-Kjeldahl procedure, available phosphorus ($mg \cdot kg^{-1}$) was assessed using the AS-10 method based on the Olsen procedure (Olsen and Sommers, 1982), available potassium ($mg \cdot kg^{-1}$) was determined by the AS-12 method, exchangeable cations – calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K) – were measured using the AS-12 method with ammonium acetate. Finally, the soil texture class was determined following the AS-09 methodology based on the Bouyoucos procedure (Semarnat, 2002).

Table 1. Description of the assessed species and their degree of desirability for grazing in central Peru

Species	Family	Animal species	Desirability degree
Festuca dolichophylla	Poaceae	Cattle, Sheep, Alpacas	1, 2, 2
Cinnagrostis vicunarum	Poaceae	Cattle, Sheep, Alpacas	2, 2, 2
Jarava ichu	Poaceae	Cattle, Sheep, Alpacas	2, 3, 2

Note: 1 – desirable; 2 – moderately desirable; 3 – undesirable.

Nutritional quality analysis – production potential

Tissue samples from the aerial parts of the studied species (*F. dolichophylla, J. ichu*, and *C. vicunarum*) were collected, dried, and ground. The percentages of dry matter, total protein, calcium, and phosphorus were determined using AOAC methods 990.03, 950.46, 984.13, 927.02, and 965.17, respectively (AOAC, 2005). Additionally, the in vitro organic matter digestibility (IVOMD) was estimated using the ANKOM N° 3 – in vitro digestibility method with the Daisy Incubator, based on the Tilley and Terry modified procedure (Goering and Soest, 1970; Adesogan, 2005). Finally, the metabolizable energy content was estimated using the ME equation (MJ·kg^{-1} dry matter) = 0.16x IVOMD (Geenty and Rattray, 1987).

Statistical analysis

Statistical analysis was performed by R version 3.8 (R Core Team, 2020). Soil variables, including pH, electrical conductivity (EC, mS·m^{-1}), organic matter (OM, %,), nitrogen (N, %), phosphorus (P, mg·kg^{-1}), potassium (K, mg·kg^{-1}), exchangeable calcium (CI-Ca, mg·kg^{-1}), exchangeable magnesium (ExC-Mg, mg·kg^{-1}), exchangeable sodium (ExC-Na, mg·kg^{-1}), and exchangeable potassium (ExC-K, mg·kg^{-1}), as well as foliar variables such as dry matter (DM, %), total protein (TP, %), calcium (Ca, %), phosphorus (P, %), in vitro digestibility of organic matter (IVOMD%), and metabolizable energy (ME, MJ·kg^{-1} dry matter) of grass species were analyzed using ANOVA followed by the least significant difference (LSD) test, with a significance level of 0.05. Additionally, a principal component analysis (PCA) was performed to assess the suitability of the data for factorial analysis (Kaiser, 1974). This analysis was used to identify potential associations between the plants and the evaluated variables.

RESULTS AND DISCUSSION

Soil physicochemical characteristics

Table 2 presents the physicochemical characteristics of the soil associated with the Poaceae species under study: *F. dolichophylla*, *C. vicunarum*, and *J. ichu*. Regarding pH, no significant differences were observed ($p < 0.005$) among the sampled soils, as they all fell within a range close to 7, indicating neutral soils. Similarly, in the Chinese mountains, no significant difference was found in the pH of the soil at landscape level, but alkaline soils were present (Pan et al., 2013). Although other studies in the high tropics, such as in Ecuador, show acidic soils (Adams et al., 2022). This suggests that pH does not significantly influence the studied grass species' development and/or growth. Furthermore, the biplot (Figure 2) confirms that pH is not strongly associated with specific plant species. These findings contrast with the observations of (Hinsinger et al., 2003), who reported that plant roots and associated microorganisms can alter rhizosphere pH through redox-coupled reactions. Root-induced pH changes in the rhizosphere are governed by various processes and factors, including ion uptake coupled with the release of inorganic ions to maintain electroneutrality, excretion of organic acid anions, root exudation and respiration, microbial acid production following carbon assimilation from root exudates, and plant genotype (Hinsinger et al., 2003; Turpault et al., 2007). Additionally, biological processes in plant roots can modify rhizosphere pH by releasing either protons (H^+) or hydroxyl ions (OH^-) to maintain ionic balance (Hinsinger et al., 2003; Riley and Barber, 1969). Consequently, rhizosphere pH may increase or decrease depending on the dominant process and the types of released ions (Neina, 2019). Soil pH is often described as the "master variable" due to its profound influence on numerous biological, chemical, and physical soil properties and processes that affect plant growth and biomass yield (Minasny et al., 2016).

Regarding electrical conductivity, a significant difference ($p > 0.05$) was observed for *C. vicunarum*, which exhibited the highest EC value (17.8 mS·m^{-1}), indicating greater soil salinity compared to the soils associated with the other two species, which had lower and similar EC values (9.7 and 7.8 mS·m^{-1} for *F. dolichophylla* and *J. ichu*, respectively). These findings align with those of Rao et al. (2019), who demonstrated that plant roots can influence the bulk electrical conductivity of the soil-root continuum due to root growth and development, water flow in the soil and root systems, and electrical transfer. Additionally, plant roots are known to affect bulk electrical resistivity (Maloteau et al., 2016). Soil electrical conductivity is influenced by multiple soil factors, including porosity, dissolved electrolyte concentration, texture, organic matter, moisture content, and compaction (Friedman, 2005). Moreover, Silva Filho et al. (2021) reaffirmed that increasing soil moisture content leads to higher electrical conductivity until reaching moisture saturation (35%). The EC of our three study sites (7.8 to 17.8 $m^S·m^{-1}$) was less than the 348 $mS·m^{-1}$ reported in the grasslands of the Chinese mountains (Pan et al., 2013) and slightly higher than the EC in the grasslands of Xinjiang, which also have some common genera such as *Poa* (Qian et al., 2024).

The organic matter values found (9 and 12%) are lower than those reported for the Austrian Alps (Djukic et al., 2010), but similar to those reported for the southern Tibitiana Plateau (Feyissa et al., 2023). As for the grasslands in the tropical Andes (11 °N – 56 °S), values from 0.6% to 10% were found (Alavi-Murillo et al., 2022), similar to our findings. At site level, organic matter values were relatively high across all three species, indicating OM-rich soils, ranging from approximately 9% to 12%. *C. vicunarum* and *J. ichu* exhibited slightly higher OM concentrations than *F. dolichophylla*, though the differences were not statistically significant. These OM concentrations are associated with the abundance of existing roots (Anderson et al., 2019) and the decomposition and transformation of plant detritus (litter), both above and below ground, which contribute to soil organic matter formation (Cotrufo et al., 2013). Recent studies using modern statistical approaches, such as multiple regression models (MRLs), have confirmed that OM plays a crucial role in maintaining and improving the physical, biochemical, and biological properties of soil, which is essential for sustaining agroecosystem productivity, soil quality, and soil health (Voltr et al., 2021). Moreover, OM is vital for preserving soil structural stability and fertility, making it a key factor in ensuring sustainable agricultural practices.

No significant differences were observed among the species regarding nitrogen (N), with moderate nitrogen levels ranging from 0.47% to 0.62%. These values are typical of high Andean grassland soils, consistent with the findings of Arias Arredondo et al., (2024) who reported N concentrations between 0.53% and 0.77% in high Andean soils dominated by *F. dolichophylla*, *C. vicunarum*, and *J. ichu*. The nitrogen values at our study sites are higher than the 0.15% reported in the grasslands of China (Pan et al., 2013). But lower than the values of 0.31% and 0.41% found in the Tiber and Washington mountains, respectively (Luo et al., 2023; Smith et al., 2002). N contents depend on the existing soil biota, which is responsible for its accumulation, persistence, capture, and mineralization from organic matter in the soil (Robertson and Groffman, 2024). Additionally, studies on grassland biodiversity have demonstrated the positive effects of plant diversity on soil nitrogen storage (Cong et al., 2014).

Available phosphorus levels did not show significant differences among the species, with mean values ranging from 7.7 to 9.9 $mg·kg^{-1}$. These values fall within the range reported by (Buta et al., 2019) for natural pasture soils. But lower than the values in the grasslands in Tibet and Gansu, China (Luo et al., 2023; Pan et al., 2013). Total P concentrations vary depending on soil horizon, substrate, pedogenesis, land use, and management intensity (Kruse et al., 2015). Similarly, available potassium levels showed no significant differences among the species, with mean values (Table 2) aligning with those reported by Buta et al. (2019), who found K concentrations ranging from 134.1 to 282.2 $mg·kg^{-1}$ in natural grassland soils. However, these values were higher than those found in continuously cropped grassland soils, which ranged from 36.7 to 127.5 $mg·kg^{-1}$ (Alami et al., 2021), suggesting that land use influences soil K content. Potassium exists in various forms in the soil, including mineral K, non-exchangeable K, exchangeable K, and K in solution, with its availability depending on soil type (Etesami et al., 2017).

Regarding exchangeable cations, calcium in *C. vicunarum* exhibited significant differences, with a higher concentration (6467.3 $mg·kg^{-1}$), suggesting a greater cation exchange capacity for this nutrient than the other two species. Significant differences were observed for magnesium, with *C. vicunarum* and *J. ichu* showing higher concentrations. This indicates that the soils where these species grow contain more magnesium compared to *F. dolichophylla*, which had significantly lower values. Sodium (Na) concentrations were significantly higher in *C. vicunarum* than the other species, potentially linked to its association with higher salinity soils. In contrast, potassium (K) levels showed no significant differences among species, with relatively uniform values ranging from 200 to 300 $mg·kg^{-1}$. These results align with those reported by (Tomašic et al., 2013), who found exchangeable cation concentrations in soils ranging from 18 to 8900 $mg·kg^{-1}$ for Ca^{2+}, 10.8 to

928 mg·kg^{-1} for Mg^{2+}, 58.5 to 1154.4 mg·kg^{-1} for K^+, and Na^+ levels generally below 1%, varying across different soil horizons, depths, and types. The Ca^{2+}, Mg^{2+}, and K^+ concentrations in soils remain stable over time and are generally unaffected by agricultural practices (Kopittke et al., 2017). Additionally, perennial grasslands have been shown to enhance nitrogen, potassium, calcium, magnesium, carbon levels, and cation exchange capacity in soils by 30–90% (Furey and Tilman, 2021), mainly when plant biodiversity is present, which further contributes to increased soil fertility.

The analysis revealed that *C. vicunarum* is associated with soils exhibiting higher electrical conductivity and elevated magnesium, calcium, and sodium levels. This suggests its adaptation to more soil saline conditions or soils with a higher cation concentration. In contrast, *F. dolichophylla* and *J. ichu* are found in similar soils, characterized by lower salinity levels and a more balanced cation composition, indicating their adaptation to less saline soils. These findings provide valuable insights into the ecological adaptations of these species in relation to soil properties.

A biplot analysis (Figure 2) was conducted using principal component analysis (PCA) to reduce data dimensionality and visualize the relationships between variables and observations in two dimensions (Dim1 and Dim2). The interpretation of the main elements is as follows: axes of the graph (Dim1 and Dim2): Dim1 explains 35.4% of the total data variability, while Dim2 accounts for 31.9%. Together, these two principal components explain 67.3% of the total variability. Colored points represent the Poaceae species. *C. vicunarum* clusters predominantly in the right quadrant, *F. dolichophylla* is positioned near the origin (center of the graph), and *J. ichu* is more dispersed toward the left. Arrows represent soil variable relationships, indicating how soil properties are associated with Poaceae species and their influence on the principal components. *C. vicunarum* is linked to soils with higher electrical conductivity and greater exchangeable cations concentrations, including calcium, magnesium, and sodium. The arrows point toward the area where *C. vicunarum* is clustered, suggesting a strong correlation between this species and these soil characteristics. *F. dolichophylla*, located near the origin, does not strongly associate with any specific soil variable, suggesting that its soil characteristics are intermediate compared to the other two species. *J. ichu* is associated with higher levels of exchangeable potassium and available phosphorus, as indicated by the arrows pointing toward its cluster. Additionally, this species appears to prefer soils with a slightly higher pH, as the pH arrow is also oriented toward its region in the plot.

Regarding the relationship between variables that are in close proximity, such as exchangeable calcium, exchangeable magnesium, exchangeable sodium, and electrical conductivity, a positive correlation was observed. This indicates that soils with higher electrical conductivity also tend to have elevated levels of these cations. On the other hand, organic matter and nitrogen are also

Table 2. Soil characteristics associated with Poaceae species: *Festuca dolichophylla, Cinnagrostis vicunarum, and Jarava ichu*

Characteristics	Poaceae species		
	Festuca dolichophylla	*Cinnagrostis vicunarum*	*Jarava ichu*
pH (pH units)	7.2 a	7.2 a	7.05 a
Electrical conductivity (mS·m^{-1})	9.7 b	17.8 a	7.8 b
Organic matter (%)	9.5 a	12.3 a	12.2 a
Nitrogen (%)	0.47 a	0.62 a	0.61 a
Available phosphorus (mg·kg^{-1})	9.9 a	7.8 a	7.7 a
Available potassium (mg·kg^{-1})	241.8 a	191.5 a	229.9 a
Exchangeable cations, calcium (mg·kg^{-1})	5469.3 ab	6467.3 a	5184.5 b
Exchangeable cations, magnesium (mg·kg^{-1})	396.5 b	756.0 a	654.3 a
Exchangeable cations, sodium (mg·kg^{-1})	15.8 b	29.0 a	18.4 b
Exchangeable cations, potassium (mg·kg^{-1})	293.7 a	208.4 a	253.3 a

Note: Means with different lowercase letters indicate significant statistical differences according to LSD test with a 0.05 significance level.

correlated; however, they do not appear to be strongly associated with any particular species.

The analysis revealed that *C. vicunarum* is strongly associated with soils exhibiting higher salinity and greater concentrations of exchangeable cations (Ca, Mg, Na). In contrast, *J. ichu* prefers soils with higher levels of available potassium and phosphorus and slightly lower pH. Meanwhile, *F. dolichophylla* occupies an intermediate position, showing no strong association with any specific soil variable, suggesting a greater adaptability to diverse edaphic conditions. These findings highlight how each species is adapted to different soil conditions, providing valuable insights for decision-making in managing high-Andean grasslands.

Nutritional content

Table 3 presents the nutritional characteristics results of the three Poaceae species (*Festuca dolichophylla, Cinnagrostis vicunarum, and Jarava ichu*) based on the evaluated parameters. The dry matter content was highest in *F. dolichophylla* (95.5%), although no significant differences were observed among the species. In contrast, *C. vicunarum* and *J. ichu* exhibited lower and similar dry matter values, indicating that they retain more moisture than *F. dolichophylla.*

Regarding total protein (TP), *F. dolichophylla* exhibited the highest protein content (Table 3), showing significant differences from the other species. This makes it a more nutritious option for livestock in terms of protein supply. In contrast, *C. vicunarum* and *J. ichu* had significantly lower protein levels, which is considered lower protein quality. These values fall within the range reported by Mamani-Linares and Cayo-Rojas, (2021) in Bolivia at over 4000 m.a.s.l. for two different seasons (dry and rainy) and similarly for some alpine species in India (Mugloo et al., 2023). However, in Peru, at 3800 m.a.s.l., native grass species supplemented with sheep manure during revegetation showed higher TP contents (Paredes et al., 2024) compared to the present study. Total protein is a plant component derived from nitrogen metabolism (Hawkesford et al., 2023), where nitrogen is absorbed by plant roots from the environment in the form of ammonium or nitrate. Additionally, TP plays a crucial role in ruminants' growth, production, and reproduction (Abbasi et al., 2018).

In *F. dolichophylla*, calcium content was significantly higher than in *J. ichu* but showed no significant differences compared to *C. vicunarum*, suggesting similar Ca content (Table 3). Similar to the values (0.37–0.44) found for some species in the Pyrenees mountains of Spain (Reiné et al., 2020). However, these values were lower than those reported by A. Arias Arredondo et al., (2024), who found a Ca content of 0.49% in natural highland grasslands. Similarly, the Institute of Research in Animal Science and Technology (IICAT, 2015) reported Ca values of 0.027% and 0.013% in *F. dolichophylla* and *J. ichu*, respectively. The differences

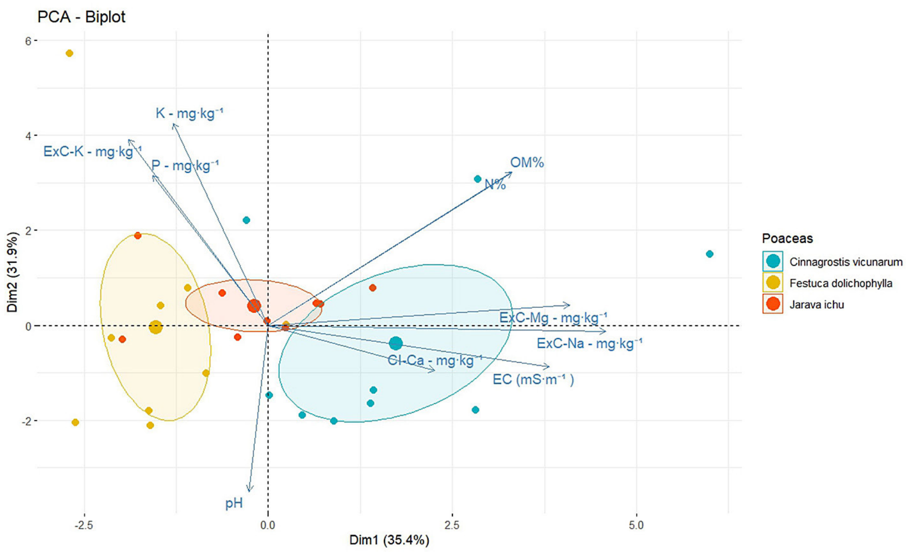

Figure 2. Biplot of PCA of the soil characteristics associated with three forage species: *Cinnagrostis vicunarum, Festuca dolichophylla, and Jarava ichu*

between studies may be attributed to ecological and physiological aspects and variations in phenology, type, and grass species. Calcium enters plants through the roots and is stored in meristematic zones and young tissues. It is considered an essential element for plant growth and development, playing a crucial role in cell wall and membrane stability and various physiological and developmental processes (Hanger, 2008; Thor, 2019). Additionally, Ca is vital for bone mineralization (bone and teeth structure), muscle contraction, and nerve impulse transmission in ruminant production (Lautrou et al., 2021; Jack et al., 2020). In contrast, our three studied species presented values lower than those reported (0.13–0.23%) for species in the Spanish Pyrenees (Reiné et al., 2020). Regarding phosphorus, no significant differences were observed among the three species (Table 3). However, although the differences were not pronounced, *F. dolichophylla* exhibited a slightly higher P content than *C. vicunarum* and *J. ichu*. These values are similar to those reported by A. Arias Arredondo et al., (2024) for natural grasslands (0.12%) but were higher than the 0.034% and 0.029% recorded by the Institute of Research in Animal Science and Technology (IICAT, 2015) in Bolivia at 3800 m.a.s.l.

Phosphorus content in plants is primarily influenced by root activity, as roots release carboxylates that solubilize P, enhancing its mobility and uptake (Lambers and Plaxton, 2015). Additionally, P is acquired from soil solution through orthophosphate (Lambers, 2022). Phosphorus is essential for all living organisms, playing a crucial role in nucleic acids and energy-transfer molecules such as adenosine triphosphate (ATP) and creatine phosphate. It is also a key mineral component of bones (Suttle, 2022). Therefore, P availability is fundamental in animal production, directly affecting its growth, health, and overall well-being (Lautrou et al., 2021).

The *in vitro* organic matter digestibility (IVOMD) of *F. dolichophylla* and *C. vicunarum* was significantly higher than that of *J. ichu*, which exhibited the lowest digestibility (Table 3). This suggests that *J. ichu* is less digestible for livestock and, consequently, provides lower nutritional value in energy utilization. Compared to forage crops such as oats, which have IVOMD values ranging from 66.5% to 87.8% (Ramírez et al., 2015; Arias Arredondo et al., 2021), *J. ichu* shows a lower digestibility potential. The IVOMD (28% to 52%) of our species was lower than the 56–73% found for other species in grasslands in the tropical Andes in Ecuador (Adams et al., 2022). IVOMD is considered an indicator of the amount of organic matter degraded by rumen microorganisms and is closely related to the energy content of forages, serving as an estimator of animal nutrient availability (Madera et al., 2013).

The metabolizable energy (ME) content was highest in *F. dolichophylla* and *C. vicunarum,* with both species showing significantly greater ME values than *J. ichu*, which exhibited the lowest energy availability (Table 3). This suggests that *J. ichu* provides less energy for livestock, making it a forage option with lower nutritional value. The ME values for *F. dolichophylla* were within the range reported by Mamani-Linares and Cayo-Rojas, (2021) of 6.9 to 9.6 $MJ \cdot kg^{-1}$ dry matter. However, the ME values for *C. vicunarum* and *J. ichu* were lower than those previously reported, which ranged from 8.4 to 10.17 $MJ \cdot kg^{-1}$ dry matter for *C. vicunarum* and from 6.07 to 6.8 $MJ \cdot kg^{-1}$ dry matter for *J. ichu* throughout the year (Mamani-Linares and Cayo-Rojas, 2021). Metabolizable energy represents the difference between the gross energy intake from ingested substrates and energy losses through feces and urine (Hall et al., 2012). Based on this definition, this study's ME values indicate the amount of energy these forage species contribute to ruminant nutrition. Additionally, ME represents the portion of dietary energy available for metabolic processes and productive activities in livestock (Arias Arredondo et al., 2021).

These results indicate that *F. dolichophylla* exhibits the highest overall nutritional quality, excelling in total protein, calcium content, digestibility, and metabolizable energy, making it an excellent forage option for livestock nutrition. *C. vicunarum* follows, with an intermediate nutritional quality due to its relatively high calcium content, IVOMD, and higher energy contribution than *Jarava ichu*. In contrast, *J. ichu* demonstrates the lowest nutritional value due to its lower digestibility percentage and energy contribution, making it a less favorable forage resource. Additionally, it is classified as a poor digestibility (PD) species for livestock. These findings are crucial for understanding the nutritional value of the most representative Poaceae species in high Andean regions, where forage availability is often limited.

Table 3. Nutritional characteristics of the three Poaceae species (*Festuca dolichophylla*, *Cinnagrostis vicunarum*, and *Jarava ichu*)

Characteristics	Poaceae species		
	Festuca dolichophylla	*Cinnagrostis vicunarum*	*Jarava ichu*
Dry matter (%)	95.50 a	94.30 a	94.60 a
Total protein (N x 6.25) (%)	10.70 a	6.80 b	7.90 b
Calcium (%)	0.36 a	0.31 ab	0.25 b
Phosphorus (%)	0.12 a	0.09 a	0.11 a
In vitro organic matter digestibility (%)	52.5 a	49.10 a	28.9 b
Metabolizable energy (MJ·kg^{-1} dry matter)	8.40 a	7.80 a	4.6 b

Note: Means with different lowercase letters indicate significant statistical differences according to LSD test with a 0.05 significance level.

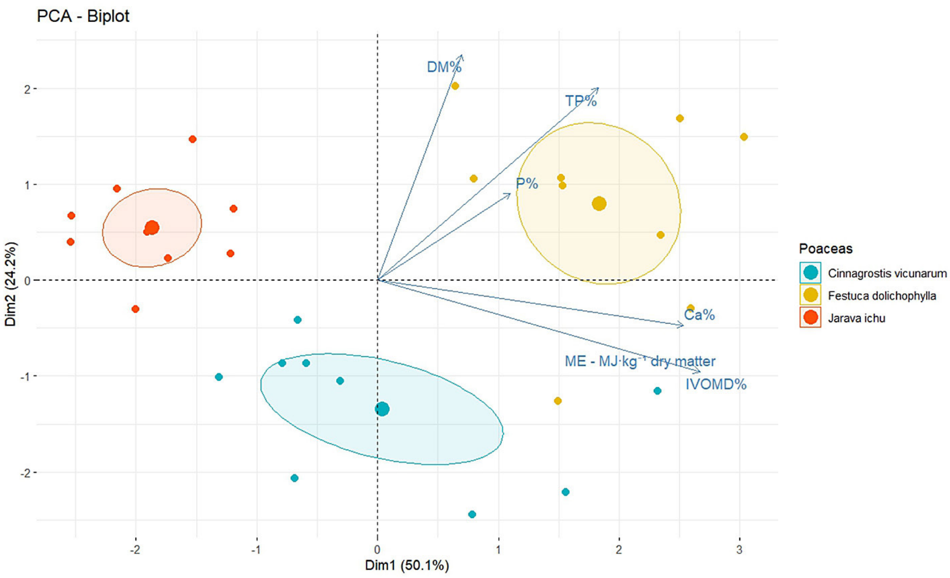

Figure 3. Biplot of a PCA illustrating three Poaceae species' nutritional characteristics: *Cinnagrostis vicunarum, Festuca dolichophylla, and Jarava ichu*

Figure 3 presents a Biplot from a PCA, which was used to reduce data dimensionality and visualize the relationships between different variables and observations. The key elements shown in Figure 3 are as follows: Dimension 1 (Dim1) accounts for 50.1% of the total data variability, while Dimension 2 (Dim2) explains 24.2%. Together, these two dimensions capture 74.3% of the total variability, a substantial proportion for a PCA analysis.

In Figure 3, the arrows represent the quantitative variables of the study, with each arrow indicating both the direction and magnitude of the correlation of a given variable with the principal components. The variables include dry matter, total protein, phosphorus, calcium, ME, and *in vitro* organic matter digestibility. Arrows that are closer together indicate positive correlations between those variables, while the length of the arrows reflects the strength of each variable's influence on the principal components. The colored points represent different grass species: *F. dolichophylla*, *C. vicunarum*, and *J. ichu*. The ellipses surrounding the colored points illustrate the variability or dispersion of observations for each grass species within the two principal dimensions. *F. dolichophylla* is more closely associated with DM, TP, P, Ca, ME, and IVOMD, as it is positioned nearer these variables. *C. vicunarum* is moderately associated with Ca, ME, and IVOMD, while *J. ichu* does not strongly correlate with any of the evaluated variables.

CONCLUSIONS

This study provides a comprehensive characterization of the soil properties and nutritional attributes associated with three high-Andean grass species (*Festuca dolichophylla, Cinnagrostis vicunarum,* and *Jarava ichu*), contributing to a better understanding of their forage value and soil-plant interactions in pasture ecosystems. Regarding the soil-plant relationship, the results indicate that *Cinnagrostis vicunarum* is associated with soils of higher electrical conductivity and greater concentrations of exchangeable cations (Ca, Mg, and Na). In contrast, *Jarava ichu* and *Festuca dolichophylla* are found in soils with lower conductivity and higher available potassium content. PCA revealed nutritional differentiation among the grass species. *Festuca dolichophylla* exhibited the highest total protein and phosphorus content, while *Cinnagrostis vicunarum* stood out regarding metabolizable energy and *in vitro* organic matter digestibility. In contrast, *Jarava ichu* presented lower values for these parameters, indicating a comparatively lower nutritional value. Overall, the findings highlight *Festuca dolichophylla* and *Cinnagrostis vicunarum* as the species with the most significant forage potential, whereas *Jarava ichu* may play a more ecological role within the ecosystem. Future research should focus on evaluating the impact of seasonality and management practices on the nutritional quality of these grass species. It is also essential to analyze their response to different fertilization strategies to enhance forage productivity. Additionally, exploring the influence of soil microbiota on nutrient uptake and the species' adaptation to stress conditions could provide valuable insights. This study serves as a foundation for further investigations to improve the quality of high-Andean pastures and promote their sustainable use in livestock production.

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