

Assessing soil and native high Andean grassland quality under grazing: A case study from the wet Puna of Peru

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Abstract

High Andean grasslands are vulnerable to changes in their nutritional quality and carbon sequestration capacity, especially in grazing systems. This study evaluated soil quality and native grasses by measuring carbon, physicochemical parameters, and the nutritional quality of predominant species in the wet Puna of Junín, Peru. Significant differences were found in carbon storage and nutritional quality across different grazing grassland sites. Soil carbon levels were consistently high across all sites, with significant concentrations at San Pedro de Cajas ($14.26\% \pm 11.7\%$; $p < 0.05$), and its carbon stock (210.7 ± 111.3 Mg/ha) exceeded that of Junín (+68%) and Ulcumayo (+107%). Also, the flat topography at this site is presumed to have influenced its soil fertility. No adverse relationship was observed between carbon content and animal units, regardless of continuous or rotational grazing system, and a strong negative Pearson correlation ($r = -0.84$) between total carbon and bulk density indicated the prevalence of organic materials and no soil compaction. It emphasizes how landscape features affect soil quality and ecosystem processes. The protein content of key species exhibited a strong Pearson correlation with plant phosphorus ($r = 0.93$), digestible organic matter (DOM), and metabolizable energy (ME; $r = 0.75$). The Redundancy Analysis (RDA) showed that plant functional traits are driven by chemical and physical gradients, underscoring the combined effects of nutrient availability and site constraints on pasture productivity and forage quality. Among native grasses, *Cebadilla* (*Calamagrostis vicunarum* [Wedd.] Pilg.) emerged as the most favorable option for animal nutrition and exhibited a significantly higher crude protein content ($8.23\% \pm 0.89\%$), Metabolizable energy value (8.16 MJ/kg), and C/N ratio (~ 40). Future research should focus on linking soil and forage quality with animal physiological responses to improve understanding of grazing impacts and guide sustainable management in high-altitude grasslands.

KEYWORDS

forage quality, grazing management, soil carbon, stock carbon, stocking rate

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1 | INTRODUCTION

The high Andean ecosystems, renowned for their rich biodiversity and crucial role in providing ecosystem services, hold paramount significance for environmental balance and the well-being of usufructuary communities reliant on them (Alavi-Murillo et al., 2022; Mosquera et al., 2022). Within this natural collage lies the wet and dry Puna, which covers the largest area by far (498,095 km² or 85% of high Andean grasslands), extending from north-central Peru to western Bolivia; however, only a few studies (6%) have been conducted in these ecosystems, primarily in the central area of Peru (Mosquera et al., 2022).

The Puna ecosystem provides essential services and sustenance for local populations and wildlife. Among these, it notably includes the capacity for carbon sequestration, a fundamental aspect in mitigating climate change and curbing carbon emissions (Madrigal-Martínez & Miralles i García, 2019). Livestock pressure can generate changes in the soil's structure and function influencing its microbiota; a previous study has observed that the abandonment of extensive grazing had both direct and indirect impacts on microbial communities, reducing the relative abundance and enzyme activity (Serrano et al., 2024). However, it was observed that, in grassland ecosystems, plants adjust the composition of root metabolites to regulate beneficial microorganisms, and these strategies vary under different grazing pressures. Under light grazing, it is suggested that root metabolites, particularly amino acids such as L-histidine, may regulate saprophytic fungi involved in nutrient transformation and energy cycling, thereby enhancing plant growth. Under heavy grazing, however, plants appear to adjust the production of metabolites including amino acids, short-chain organic acids, and alkaloids, secreting them to stimulate the proliferation of plant growth-promoting rhizobacteria and fungi, which in turn help mitigate grazing stress and strengthen plant defenses (Yuan et al., 2023). These indicate an effect of grazing on soil fertility, forage quality, and microbial communities, potentially compromising key ecosystem services such as nutrient cycling, carbon storage, and climate change mitigation.

Previous studies have communicated various systems, from intensive rotational grazing to extensive continuous grazing systems, each with unique impacts on productivity, soil health, biodiversity, and animal welfare (Teague & Kreuter, 2020). In the Andean Puna ecosystems, there is a coevolution and interdependence between the grasslands and livestock grazing. Grazing by camelids in the Puna is expected to have a lesser impact on soil and the vegetation, which may be partly explained by camelid traits, such as their padded feet, which cause less soil disturbance, and their foraging habit of consuming mainly the upper parts of plants (Duchicela et al., 2024).

Grasslands with livestock presence constitute highly diverse ecosystems, as livestock promotes interspecific competition and prevents any single species from becoming particularly dominant within the system. Also, herders use various techniques to manage grassland resources, such as mobility, grazing, corralling, and pasture reserves; in the long term, they contribute to improving, conserving, and using the biodiversity of grasslands (Seid et al., 2016).

In Peru, livestock consists mainly of camelids (55.9%), followed by sheep and goats (16.2%), cattle (14.7%), and equines (1.47%).

Camelids dominate the Puna of the central Andes, where their grazing has been associated with reduced graminoid cover, biomass, SOC, and plant diversity, though evidence is less consistent, possibly due to their long coevolution with native vegetation (Duchicela et al., 2024).

The diversity of native forage species, such as *Cebadilla* (*Calamagrostis vicunarum* [Wedd.] Pilg.), *Chillihua* (*Festuca dolichophylla* J.Presl), *Crespillo* (*Festuca rigescens* [J.Presl] Kunth), and *Ichu* (*Stipa ichu* [Ruiz & Pav.] Kunth), plays a key role in the availability of livestock feed and the stability of the ecosystem. The dominant grass species can also influence the forage quality and the soil's capacity to store carbon (Greenwood & McKenzie, 2001). In terms of livestock fauna, the Puna of Junín is home to Hybrid alpaca (*Lama glama* × *Vicugna pacos*), *Huacaya alpaca* (*V. pacos* Linnaeus, 1758), sheep (*Ovis aries* Linnaeus, 1758), and cattle (*Bos taurus* Linnaeus, 1758), species that have varying impacts on the soil and pasture regeneration; it has been reported that soil compaction varies depending on livestock density and animal type, which can affect water infiltration and carbon retention. The correlations between soil health and livestock species diversity still require further exploration, particularly regarding their effects on the soil microbial community and carbon sequestration efficiency (Southorn & Cattle, 2004).

Grassland productivity is strongly influenced by management practices; however, the outcomes of implementing identical management strategies can vary considerably depending on environmental factors such as climate, soil characteristics, landscape position, and the composition of the plant community. Consequently, interpreting research findings related to the effects of land use types and their associated practices must be considered within the context of each specific site (Mayel et al., 2021).

This study evaluates soil properties and native grass species to assess carbon stocks, physicochemical characteristics, and forage nutritional quality in grazed high Andean grasslands of Peru, providing a basis for sustainable management strategies that enhance environmental and economic benefits while minimizing adverse impacts.

2 | MATERIALS AND METHODS

2.1 | Study site

The study was conducted in the central highlands of Peru, located in the Puna natural region, in representative areas in Junín (11°9'53"S, 75°55'51"W; 4379 m above sea level) and Ulcumayo districts (11°3'0.5"S, 75°53'59.6"W; 4384 m.a.s.l.) in Junín province. In Tarma, specifically in San Pedro de Cajas peasant community (11°11'14.1"S, 75°51'31.9"W; 4378 m.a.s.l.), and in the Palcamayo district, collaboration was conducted with the Shacamarca peasant community (11°11'51"S, 75°49'15.6"W; 4296 m.a.s.l.).

The dominant landscape in the Puna is the natural grassland ecosystem, where the prevalent vegetation includes bunchgrass ("pajonal") and Puna grass ("césped de puna"). The seasonal vegetation comprises tussock grasslands, some shrublands, and open rocky areas, interspersed with peat bogs and fens (often beneath glaciers) and some forested areas. It is important to mention that the locations where soil and foliar

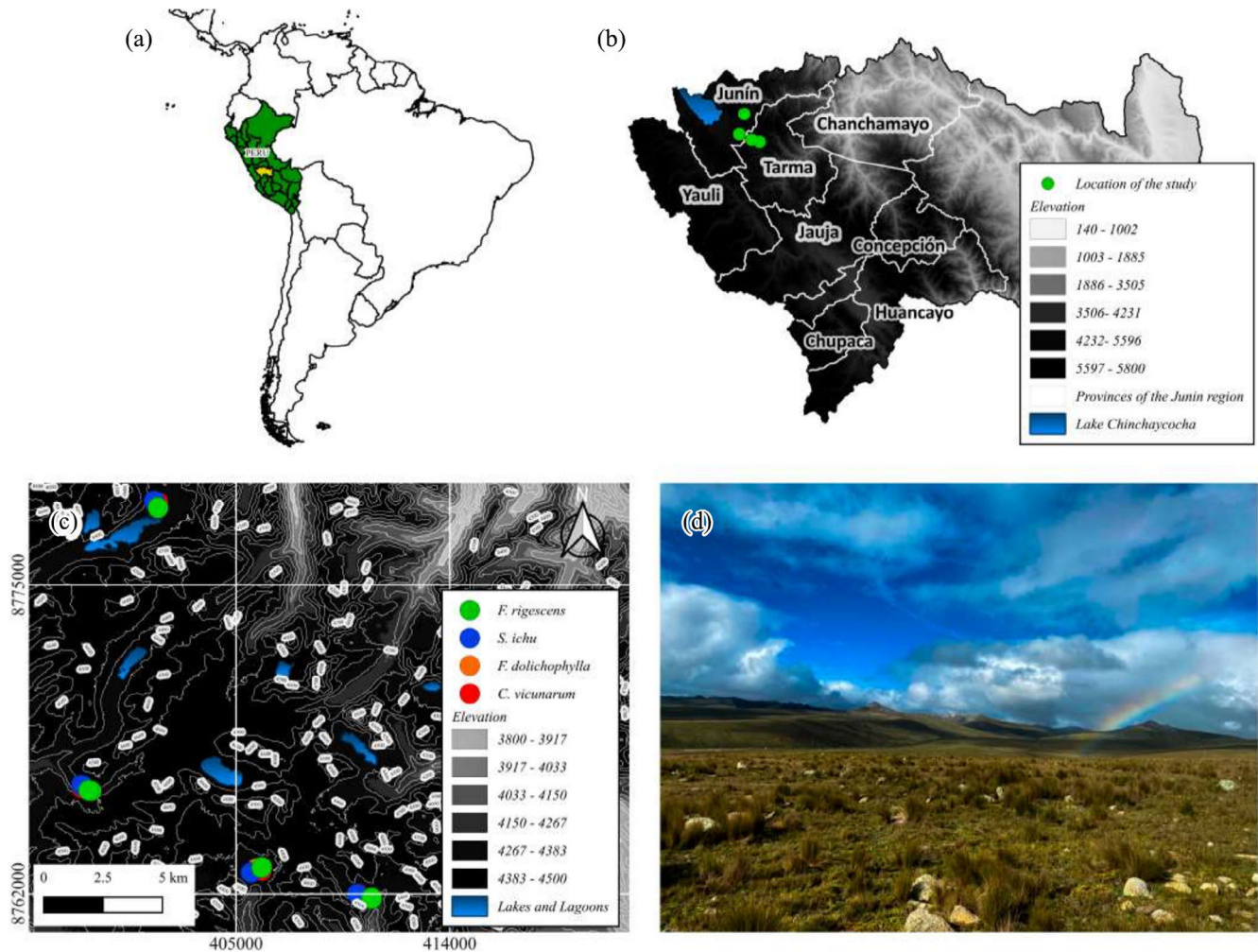


FIGURE 1 Study area in wet Puna. (A) Geographical position of Perú in South America; (B) Junín and Tarma provinces of Junín department; (C) sampling points location; and (D) predominant ecosystem in the study area: Pajonales and Puna grass.

samples were taken were within a radius of 500 m from water sources (lakes, ponds, streams, and springs). Also, regarding the slope, Junín presented 24%, Ulcumayo 4%, San Pedro de Cajas 3%, and Palcamayo 18%; therefore, it can be stated that the study sites have water circulation in the meadows, avoiding floods or waterlogging, thus enabling proper soil aeration and adequate root development (Figure 1).

2.2 | Weather and climate conditions

The data covered the period from January to December 2023; the minimum temperature was -4.1°C , and the maximum reached 14.2°C . In the dry season (June to October), the average temperature was 6.3°C , and during the rainy season (November to May), 7.3°C . Annual precipitation ranged from 650 to 1200 mm, with a dry season average of 134 mm and a rainy season average of 591 mm. The relative humidity ranged between 74% and 84%. The data were obtained from the Junín meteorological station operated by SENAMHI ($11^{\circ}8'34.8''\text{S}$, $-75^{\circ}59'19.7''\text{W}$; 4101 m.a.s.l.; SENAMHI - Estaciones, 2024).

2.3 | Sampling

Representative soil samples were collected, ensuring adequate coverage and considering spatial variability. To analyze the interrelationship between soil and plant species, the study began with the identification of the predominant vegetation in the high-Andean grasslands, selecting *C. vicunarum*, *F. dolichophylla*, *F. rigescens*, and *S. ichu* due to their dominance in the study area. The plants were carefully extracted from the roots to the stems and leaves by digging into the soil to prevent the loss of underground structures relevant to the analysis. At each site, eight composite samples for soils and plants were collected, totaling 32 samples, ensuring the representativeness of each grazing area. Each plant composite sample consisted of several individuals of the same species within a defined area, following previous methodologies that have been proven sufficient for assessing the nutritional quality of forage species in high-Andean ecosystems (Coêlho et al., 2018). Subsequently, two replicates of each sample were taken to ensure the accuracy of the analyses.

2.4 | Grassland condition

It was evaluated according to the floristic composition of desirable species index for animal feeding (sheep, cattle, and alpaca), fodder index, cover index, and plant vigor, which indicated a score from each study location (Siffredi et al., 2015). The study used the line transect method (100 m). Vegetation readings and assessments of litter, moss, rocks, erosion pavement, and bare soil were performed using a census ring along the transect. Additionally, it measured the plant vigor for sheep and cattle (Arce-Inga et al., 2017; Siffredi et al., 2015). Furthermore, *C. vicunarium*, *F. dolichophylla*, *F. rigescens*, and *S. ichu* were considered because they were predominant to assess carbon content and nutritional quality in native grasslands (Table S1).

2.5 | Soil and plant analysis of grazing grassland

Soil total carbon (TC) was determined by dry combustion in an Elemental Analyzer LECO 828 (Leco Inc., St. Joseph, MI, United States), and for calculating Carbon Stock, bulk density (BD) was measured by the core method (Al-shammary et al., 2018); the cylinder volume was 196.25 cm³, 2.5 cm (radius), 10 cm (height), and the depth for each sampling point (20–35 cm). We analyzed soil fertility through parameters like pH (inoLab[®] pH 7310); electrical conductivity (EC; Kargas et al., 2022); extractable potassium (K_{soil}) by ammonium saturation, subsequently analyzed using inductively coupled plasma optical emission spectrometry (ICP-OES) in accordance with EPA Method 6010D (EPA Method 6010D, 2018), and phosphorus (P_{soil}) by Olsen (neutral-alkaline soils; Recena et al., 2016, or Bray-Kurtz method [acid soils]; Yusuf et al., 2023). Also, the nutritional quality of key species was determined by collecting, drying, and grinding complete plant tissue samples. It was analyzed for total carbon (CC) by loss-on-ignition (LOI) method (Carolan & Fornara, 2016), dry matter percentage (DryBio; Rocha et al., 2017), total protein (Wei et al., 2020), calcium (Ca), and phosphorus (P) (Grzegorzczak et al., 2017). Additionally, the in vitro digestibility of organic matter (DOM) was estimated using Ankom method No. 3 with the Daisy Incubator, Tilley, and Terry modified (Adesogan, 2005; Goering & Soest, 1970). Finally, metabolizable energy (ME) was calculated using the equation ME (MJ/kg DM) = 0.16 × DOM (g/kg DM; Geenty & Rattray, 1987).

2.6 | Statistical analysis

The collected data underwent processing through a non-parametric Kruskal–Wallis ANOVA. The comparisons between sampling locations and key species employed the Dunn test with Benjamini–Hochberg correction from the rstatix package (Kassambara, 2023). Both tests considered a significance level of $p < .05$. Principal component analysis (PCA) was applied to environmental variables to identify dominant edaphic gradients and assess multicollinearity. Before constrained ordination, a detrended correspondence analysis (DCA) was used to assess gradient lengths in the response matrix. The short length of the first DCA axis (<2 SD units) indicated linear responses, and redundancy analysis (RDA) was therefore selected. The RDA was performed

to evaluate how plant nutrition traits responded to these dominant edaphic gradients. Multicollinearity among predictors was evaluated using variance inflation factors (VIF), with all retained variables showing VIF values <5. A VIF > 5 was considered highly collinear and excluded from subsequent analyses. Model, term, and axis significance were tested using permutation tests (999 permutations). All analyses were conducted in R using the vegan package (R Core Team, 2025).

3 | RESULTS

3.1 | Socioeconomic dimension of grazing livestock system

The grazing systems in Junín and Ulcumayo were private, whereas those in San Pedro de Cajas and Palcamayo were communal. In Junín, labor was provided by the owner; in Ulcumayo, by support staff or part-time workers; personnel were hired in San Pedro de Cajas and Palcamayo. Regarding the main activity, which was mixed cattle ranching, Junín raised Hybrid cattle (Criollo cattle × Brown Swiss cattle) with 33.6 animal units (AU), which were raised on 50 ha on a rotational grazing basis with three rest paddocks; Ulcumayo had Criollo cattle (*B. taurus* Linnaeus, 1758) with 23.1 AU, Criollo sheep (*O. aries* Linnaeus, 1758) with 32.9 AU and Hybrid alpaca (*L. glama* × *V. pacos*) and *Huacaya alpaca* (*V. pacos* Linnaeus, 1758) with 26.6 AU, in 120 ha with continuous grazing without rest throughout the year; San Pedro de Cajas had Hybrid cattle (Criollo cattle × Brown Swiss cattle) with 39.9 AU and Hybrid sheep (Criollo sheep × Corriedale sheep) with 94.7 AU in 100 ha where grazing was rotative and continuous; at last, Palcamayo had Hybrid cattle (Criollo cattle × Brown Swiss cattle) with 9 AU, Hybrid sheep (Criollo sheep × Corriedale sheep) with 101.4 AU and *Huacaya alpaca* with 49.1 AU, in 100 ha where grazing was continuous without rest during the year (Table S2).

A specialist from the Junín agricultural agency in the beef chain mentioned different forms of grazing: In cattle, plots are divided into two or more than three paddocks, and this grazing management is generally developed in producers dedicated to milk production. Likewise, the director of the agricultural agency Junín mentioned that the raising of sheep and alpaca in the province involves continuous and rotational grazing. On the other hand, regarding the economic aspect, the main source of income is the sale of milk and meat, followed by alpaca fiber and sheep wool; however, it is generally for subsistence.

3.2 | Grassland condition

Evaluating pasture condition was key to determining how livestock grazing influenced high-Andean grasslands (Bardgett et al., 2021; Jacobo et al., 2006), which refers to the overall health status of the field. This condition was determined through an average analysis of floristic composition and plant species, classified according to their desirability for livestock, including sheep, cattle, and camelids. The classification consisted of five levels: excellent, good, fair, poor, and very poor, measured on a numerical scale ranging from 0% to 100% (Arturo Flórez &

TABLE 1 Soil parameters related to carbon storage and fertility.

	TC (%)	pH	BD (g/cm)	EC (dS/m)	Carbon stock (Mg/ha)	P _{soil} ^a (mg/kg)	K _{soil} ^a (mg/kg)
Sites (A)							
San Pedro de Cajas	14.26 ± 11.7 a	6.78 ± 0.4 a	0.78 ± 0.4 b	0.73 ± 0.5 a	210.7 ± 111.3 a	43.89 ± 26.4 a	222.31 ± 147.7 a
Palcamayo	6.68 ± 3.7 b	5.98 ± 1.1 a	1 ± 0.3 a	0.54 ± 0.5 a	154.02 ± 49.1 ab	39.46 ± 21.1 a	102.19 ± 36.2 b
Junín	4.44 ± 0.6 b	5.14 ± 0.4 b	1.16 ± 0.1 a	0.24 ± 0.1 b	124.96 ± 23.5 bc	13.51 ± 8.2 b	252.35 ± 182.1 a
Ulcumayo	4.17 ± 1.1 b	5.06 ± 0.5 b	1.02 ± 0.2 a	0.33 ± 0.2 a	102.02 ± 18.6 c	26.51 ± 33.9 b	291.68 ± 228.4 a
Key species (B)							
<i>C. vicunarum</i>	5.43 ± 3.6 bc	5.46 ± 0.8 a	1.15 ± 0.2 a	0.33 ± 0.2 b	145.49 ± 88.4 a	50.88 ± 26.6 a	261.8 ± 169.8 a
<i>F. dolichophylla</i>	12.97 ± 12.2 a	5.90 ± 0.9 a	0.74 ± 0.3 b	0.76 ± 0.5 a	171.64 ± 104.1 a	15.66 ± 10.8 b	310.38 ± 236.6 a
<i>F. rigescens</i>	6.77 ± 3.1 ab	6.14 ± 1.0 a	0.93 ± 0.2 b	0.55 ± 0.4 ab	145.86 ± 42.8 a	23.04 ± 24.6 b	206.01 ± 123.5 a
<i>S. ichu</i>	4.38 ± 2 c	5.45 ± 1.0 a	1.13 ± 0.1 a	0.20 ± 0.1 c	128.7 ± 35.6 a	33.80 ± 28.0 b	90.34 ± 33 b
Sites (A)	***	***	***	*	***	***	*
Key species (B)	***	ns	***	***	ns	**	***
Sites (A) x key species (B)							
Junín							
<i>C. vicunarum</i>	4.42 ± 0.3 ab	5.7 ± 0.3 a	1.11 ± 0.1 b	0.31 ± 0.1 a	97.98 ± 11.1 b	24.25 ± 7.8 a	536.55 ± 32.3 a
<i>F. dolichophylla</i>	4.81 ± 0.3 a	4.9 ± 0.1 a	1.13 ± 0 b	0.24 ± 0.1 ab	148.83 ± 19.9 a	11.15 ± 2.1 ab	169.05 ± 94.5 b
<i>F. rigescens</i>	4.95 ± 0.2 ab	4.9 ± 0.2 a	1.13 ± 0 b	0.24 ± 0.1 ab	139.34 ± 0.7 a	12.6 ± 5.8 ab	197.65 ± 79.6 ab
<i>S. ichu</i>	3.57 ± 0.3 b	5.05 ± 0.4 a	1.28 ± 0 a	0.18 ± 0 b	113.69 ± 7.7 ab	6.05 ± 1.8 b	106.15 ± 11.5 b
Palcamayo							
<i>C. vicunarum</i>	3.79 ± 0.3 ab	5.15 ± 0.4 b	1.26 ± 0.1 a	0.22 ± 0.1 ab	133.83 ± 22.5 a	58.4 ± 7.7 a	146.05 ± 31 a
<i>F. dolichophylla</i>	9.07 ± 2.9 a	6.25 ± 1.1 ab	0.8 ± 0.1 ab	0.66 ± 0.5 ab	162.79 ± 59.4 a	26.85 ± 15.1 b	88.95 ± 7.9 b
<i>F. rigescens</i>	10.8 ± 0.9 a	7.4 ± 0 a	0.73 ± 0 b	1.12 ± 0.2 a	205.13 ± 41.6 a	14.8 ± 0.1 b	99.25 ± 13.8 ab
<i>S. ichu</i>	3.09 ± 0 b	5.1 ± 0.1 b	1.2 ± 0 a	0.16 ± 0.1 b	114.35 ± 6.7 a	57.8 ± 0.2 a	74.5 ± 38.8 b
San Pedro de Cajas							
<i>C. vicunarum</i>	9.87 ± 5.5 b	6.4 ± 0.8 a	1.11 ± 0.3 a	0.59 ± 0.3 ab	267.14 ± 101.3 a	37.5 ± 27.5 a	230.3 ± 15.5 a
<i>F. dolichophylla</i>	32.1 ± 8.7 a	6.85 ± 0.2 a	0.3 ± 0.2 b	1.54 ± 0.1 a	271.13 ± 173.3 a	16.95 ± 8.1 a	374.2 ± 212.8 a
<i>F. rigescens</i>	7.64 ± 2.4 b	6.8 ± 0.1 a	0.8 ± 0.1 ab	0.49 ± 0.1 ab	130.57 ± 9.5 a	57.75 ± 28.3 a	174.85 ± 104.3 a
<i>S. ichu</i>	7.45 ± 1.4 b	7.05 ± 0.1 a	0.93 ± 0.1 a	0.31 ± 0.3 b	173.98 ± 46.1 b	63.35 ± 8.4 a	109.9 ± 44.6 a
Ulcumayo							
<i>C. vicunarum</i>	3.66 ± 0.3 ab	4.6 ± 0.1 a	1.14 ± 0 ab	0.21 ± 0 a	83.04 ± 6.5 a	83.35 ± 1 a	134.3 ± 20.2 bc
<i>F. dolichophylla</i>	5.9 ± 0.2 a	5.6 ± 0.1 b	0.75 ± 0 a	0.59 ± 0 b	103.83 ± 10.3 ab	7.7 ± 0.3 ab	609.3 ± 94.8 a
<i>F. rigescens</i>	3.71 ± 0.7 ab	5.45 ± 0.1 ab	1.07 ± 0.1 ab	0.38 ± 0.1 ab	108.39 ± 20.6 ab	7 ± 0.3 b	352.3 ± 117.2 ab
<i>S. ichu</i>	3.43 ± 0.3 b	4.6 ± 0.1 a	1.11 ± 0.1 b	0.14 ± 0 a	112.81 ± 21.4 b	8 ± 1.4 ab	70.8 ± 11.4 c

Note: The data in the table expresses the average and standard deviation ($\mu \pm \sigma$) of the evaluated parameters. Those values with different letters in the same column indicate significant differences between the treatments ($p < 0.05$).

Abbreviations: BD, bulk density; EC, electrical conductivity; ns, no significant difference; TC, total carbon.

^aExtractable element.

*Significant difference $p < 0.1$.

**Significant difference $p < 0.05$.

***Significant difference $p < 0.01$.

Malpartida, 1987; Flores Cochachin et al., 2023). This assessment was essential for determining the carrying capacity of grasslands.

Condition assessment ranged from poor to regular; Palcamayo and Ulcumayo were in poor conditions; Junín and San Pedro de Cajas showed pastures in regular condition. In Junín, the key species was *F. dolichophylla* because cattle raising predominated in this place;

however, for Ulcumayo, Palcamayo, and San Pedro de Cajas, *C. vicunarum* was considered because sheep farming was predominant (Table S3).

The stocking rate showed that the current load (AU/ha/year) was 0.7 for Junín and Ulcumayo, 1.3 for San Pedro de Cajas, and 1.6 for Palcamayo, whereas the recommended load was 0.4 for Junín and San

Pedro de Cajas and 0.1 for Ulcumayo and Palcamayo. The sustainable stocking rate for the livestock farms indicated a negative balance, indicating that the current load was above the value recommended (Table S4).

3.3 | Soil carbon storage and fertility

Differences in TC and Carbon Stock among sites were statistically significant. In general, the TC was high at all locations but considerably higher at San Pedro de Cajas, over Palcamayo (+114%), Junín (+221%), and Ulcumayo (+242%), and the Carbon Stock was higher than Junín (+68%) and Ulcumayo (+107%). The soil pH of San Pedro de Cajas was neutral and moderately acidic for Palcamayo; however, in Junín and Ulcumayo, the soils were strongly acidic. All the sites were non-saline for the low values in EC. The phosphorus test in San Pedro de Cajas was Olsen and reported a high content, and according to the test Bray, applied for Palcamayo and Ulcumayo, they had high content, and for Junín, it was medium. The available potassium in Palcamayo was low, medium for San Pedro de Cajas, and high for Junín and Ulcumayo (Hazelton & Murphy, 2016). A higher content of soil nutrients was associated with the species *C. vicunarium* and *F. dolichophylla*. Also, the soil with *F. dolichophylla* had higher TC (Table 1). PCA of standardized environmental variables revealed two dominant gradients. The first axis (PC1, 45.9%) represented a soil chemical fertility gradient, positively associated with pH, electrical conductivity, and total carbon, and negatively associated with altitude and bulk density. The second axis (PC2, 25.3%) reflected a nutrient availability gradient, mainly driven by soil phosphorus and potassium. The study sites were separated according to their edaphic characteristics. The PCA biplot revealed partial correlations among environmental variables, such as the strong positive association between EC and total carbon. However, variables were not perfectly aligned and loaded on different axes, indicating shared but non-redundant information. This structure suggests the presence of ecologically meaningful gradients rather than extreme multicollinearity (Table S5 and Figure 2).

3.4 | Nutritional quality of key species

Plant Elemental Analysis indicated a significantly lower carbon content for *C. vicunarium* compared with *F. dolichophylla* (+3.13%) and *S. ichu* (+3.09%) grasslands. There were significant differences according to the evaluation sites, with the highest contents in Junín differing from Ulcumayo (+2.45%) and Palcamayo (+5.03%), and San Pedro de Cajas from Palcamayo (+3.68%). In dry biomass, *C. vicunarium* and *S. ichu* presented the highest content in comparison with *F. dolichophylla* (+9.78%, +7.62%), and *F. rigescens* (+10.63%, +8.45%). Regarding protein, the highest content was measured in *C. vicunarium* over *F. dolichophylla* (+116%), *F. rigescens* (+85.36%), and *S. ichu* (+145.67%). No significant differences were observed in calcium; however, phosphorus concentrations were significantly

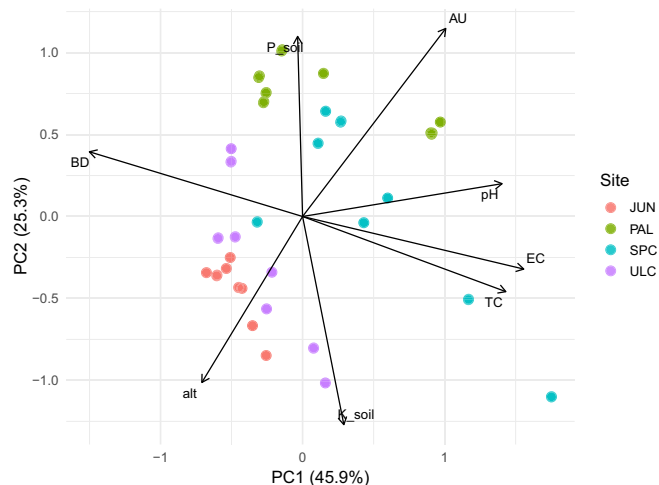


FIGURE 2 Biplot resulting from principal component analysis (PCA) of soil parameters at the sites. alt, altitude; AU, animal unit; BD, bulk density; EC, electrical conductivity; JUN, Junín; K_{soil}, extractable potassium; P_{soil}, extractable phosphorus; PAL, Palcamayo; SPC, San Pedro de Cajas; TC, total carbon; ULC, Ulcumayo.

higher in *C. vicunarium* than in the other species, and this species also exhibited greater in vitro DOM and ME compared with *F. dolichophylla* and *S. ichu* (Table 2). Protein content in plant tissues is typically estimated by multiplying nitrogen content by 6.25, assuming that protein is composed of approximately 16% nitrogen (Mariotti et al., 2008). Based on this calculation, the nitrogen content and C/N ratios for the studied species are as follows: *C. vicunarium* (1.32% N; ~39.6 C/N), *F. dolichophylla* (0.61% N; ~88.5 C/N), *F. rigescens* (0.71% N; ~73.6 C/N), and *S. ichu* (0.54% N; ~99.9 C/N).

3.5 | Relationship between soil parameters and plant nutritional quality

The EC presented a VIF = 6.76; it was considered highly collinear and excluded from RDA (Table S7). Then, the RDA revealed that soil physicochemical properties, animal unit, and altitude jointly explained 56.5% of the variation in plant nutritional and biomass-related traits. The first two RDA axes accounted for 48.9% of the total variance and 86.7% of the constrained variance, indicating a strong underlying environmental gradient. Also, the model was highly significant ($F = 10.371$, $p = .001$). The final VIF analysis indicated low multicollinearity among explanatory variables, supporting the robustness of the model (Table S8). RDA1 separated sites with higher altitude and bulk density from those with higher soil fertility. RDA2 further distinguished sites according to soil chemical quality. Plant response variables showed clear associations with environmental gradients, highlighting the combined role of nutrient availability and soil physical conditions in structuring plant responses. Calcium and DOM were associated with AU, pH, and total soil carbon (TC), indicating greater organic matter accumulation under chemically more favorable soil

TABLE 2 Carbon and nutritional quality of four native grassland species.

Specie	CC (%)	DryBio (%)	Protein (%)	Ca _{grass} (%)	P _{grass} (%)	DOM (%)	ME (MJ/kg)
<i>C. vicunarum</i>	52.37 ± 1.5 b	77.33 ± 5.29 a	8.23 ± 0.89 a	0.26 ± 0.05 a	0.17 ± 0.03 a	50.99 ± 3.9 a	8.16 ± 0.63 a
<i>F. dolichophylla</i>	54.01 ± 1.11 a	70.44 ± 7.86 b	3.81 ± 0.42 b	0.25 ± 0.13 a	0.06 ± 0.02 b	42.42 ± 4.77 bc	6.79 ± 0.76 bc
<i>F. rigescens</i>	52.27 ± 3.26 ab	69.9 ± 5.28 b	4.44 ± 0.74 b	0.22 ± 0.09 a	0.08 ± 0.03 b	46.6 ± 3.78 ab	7.46 ± 0.61 ab
<i>S. ichu</i>	53.99 ± 1.43 a	75.81 ± 5.99 a	3.35 ± 0.98 b	0.19 ± 0.08 a	0.07 ± 0.04 b	39.31 ± 6.29 c	6.29 ± 1.01 c
Junín	54.3 ± 0.8 a	72 ± 3.9 b	4.8 ± 2.1 b	0.2 ± 0 ab	0.1 ± 0 a	43.1 ± 7.5 ab	6.9 ± 1.2 ab
San Pedro de Cajas	53.6 ± 2.1 ab	76.3 ± 5.8 a	5.5 ± 2.1 a	0.3 ± 0.1 a	0.1 ± 0 a	48.6 ± 2.8 a	7.8 ± 0.5 a
Ulcumayo	53 ± 1.8 bc	75.1 ± 7.2 ab	4.1 ± 1.8b	0.2 ± 0.1b	0.1 ± 0 a	41 ± 6.1 b	6.6 ± 1 b
Palcamayo	51.7 ± 2.7 c	70.1 ± 8.6 b	5.4 ± 2.3 a	0.3 ± 0.1a	0.1 ± 0.1 a	46.6 ± 6 ab	7.5 ± 1 ab

Note: The data in the table expresses the average and standard deviation ($\mu \pm \sigma$) of the evaluated parameters. Those values with different letters in the same column indicate significant differences between the treatments ($p < 0.05$).

Abbreviations: CC, carbon content; DOM, in vitro digestibility of organic matter; DryBio, dry biomass; ME, metabolizable energy.

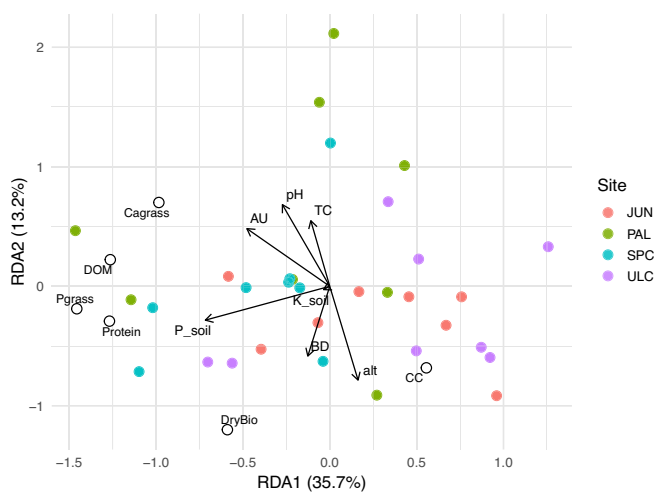


FIGURE 3 Redundancy analysis (RDA) biplot showing the relationships between soil chemical and physical parameters (arrows) and nutritional quality of key grassland species (circles). alt, altitude; AU, animal unit; BD, bulk density; Ca_{grass}, plant calcium; CC, plant carbon content; DOM, in vitro digestibility of organic matter; DryBio, dry biomass; JUN, Junín; K_{soil}, extractable potassium; P_{soil}, extractable phosphorus; P_{grass}, plant phosphorus; PAL, Palcamayo; protein, plant protein; SPC, San Pedro de Cajas; TC, total carbon; ULC, Ulcumayo.

conditions. In contrast, plant phosphorus (P_{grass}) and Protein showed a strong association with soil phosphorus (P_{soil}), suggesting a direct nutritional control of phosphorus availability on forage quality (Figure 3).

4 | DISCUSSION

Respecting soil carbon, San Pedro de Cajas exhibited a significantly higher content of TC, a characteristic feature of soils with a substantial percentage of undecomposed, semi-decomposed plant material and leaf litter; this occurrence is typical in areas where cold temperatures and continuous wet conditions hinder the decomposition of

organic matter. Previous studies in the provinces of Junín and Yauri found a TC ~ 4.82% (Rolando, Dubeux, et al., 2017), which aligns with this research in Junín. Similarly, previous data referred to a comparable low bulk density and total nitrogen (TN); however, phosphorus was higher compared with preceding information in native grassland (+122%) and pasture (+64%) soils (Rolando et al., 2018). In another study, the Carbon Stock reported in Junín was 135.6 MgC/ha for cultivated pasture in the 0- to 30-cm soil profile (Rolando, Turin, et al., 2017), which was a little higher than the value in this study (124.96 MgC/ha). Also, it is important to link with the climatic conditions; some authors mentioned that in Peruvian tropical montane ecosystem, grazing had no significant effect on total soil C to 30-cm depth but produced higher respiration rates and lower SOC, supposedly because the soil temperature was a main environmental driver, and grazing intensity was below the threshold for severe degradation (Oliver et al., 2017).

Preceding research in San Pedro de Cajas reported non-saline soils with a high organic matter content; however, there is a contrast in terms of acidity between that study (pH 4–5; Ortiz-Ojeda et al., 2017) and the current findings (6.78). This difference could be related to agricultural practices that elevate the pH, such as manure incorporation (Sun et al., 2017). Despite the favorable parameters like pH in San Pedro de Cajas, decomposition did not reduce carbon contents.

In Junín and Ulcumayo, the soils were strongly acidic; this matched the low phosphorus in Junín. The bulk density for these soils ranged from 0.74 to 1.17 Mg/m³, which makes sense because organic materials have low bulk density and high porosity. It is known that incorporating manure leads to a long-term increase in SOC, total nitrogen, and electrical conductivity (Ozlu & Kumar, 2018); in this context, locations with higher overall livestock units (San Pedro de Cajas and Palcamayo) also exhibited higher values for these parameters. According to the results in this first scope, no apparent negative impact was found on the TC because of the animal unit (AU), grazing type, and use throughout the year, perhaps due to soil resilience, for example, through differential microbial populations stimulated by intensive grazing (Yuan et al., 2023).

We realized a significant negative Pearson correlation between TC and bulk density (-0.84 ; Table S9); this is frequent in most soil orders and land cover units (LCU; Al-shammari et al., 2018), and the texture was loam sand, loam, sandy loam, and sandy clay loam, which did not allow evident compaction by animal load that could be reflected in the bulk density (Fernández et al., 2020). The livestock has notable effects on the pH and chemical condition of the soil by consuming nutrients and excretion; also, preceding studies showed that heavy-grazing plots had higher pH levels, organic matter content, and soil nutrient levels than plots without grazing (Bogunovic et al., 2022). On the other hand, plant diversity and root characteristics play a fundamental role in enhancing soil physical properties. They improve soil aggregation, increase pore connectivity, and enhance water infiltration and retention. As a result, ecosystems with higher plant diversity and well-developed root systems generally exhibit healthier soils, with improved stability, porosity, and overall physical quality (Gould et al., 2016; Seifu et al., 2020). Slopes in the study areas range from moderately steep (15–30%) to slightly inclined (2–5%; FAO, 2009). This topography influences the soil's morphological and physicochemical properties; organic carbon, nitrogen, and phosphorus contents decrease as the slope increases. Conversely, flat or gently sloping areas exhibit higher organic matter content (Asmamaw & Mohammed, 2013; Dessalegn et al., 2014); this was consistent with our findings in San Pedro de Cajas, where soils exhibit greater fertility, flat areas contain higher levels of clay and organic matter due to lower sediment loss compared to steep slopes (Asmamaw & Mohammed, 2013).

Taking all factors into account, the findings suggest the soil resilience of the ecosystem, where the low temperatures did not allow a reduction in the carbon content and soil compaction, even with a more suitable pH, like that at San Pedro de Cajas, and a high stocking rate for all the sites. Also, an important geographical aspect to emphasize is that the topography promoted the accumulation of organic matter. This highlights the influence of landscape features on soil quality and ecosystem functioning.

The economic and environmental benefits of permanent grasslands in livestock farming systems need to be better assessed in terms of quantity (biomass production) and quality (DOM and crude protein content; Michaud et al., 2015). The present study obtained higher (+156%) and lower (−27%) crude protein values for *C. vicunarium* (3.21%) and *F. dolichophylla* (5.21%) compared with other research (Quispe Ramos et al., 2021); also, protein was correlated with Pgrass ($r = 0.93$) and ME ($r = 0.75$). Pgrass had a high Pearson correlation with DOM ($r = 0.78$) and ME ($r = 0.78$; Table S9). The natural high Andean grasses analyses at the Experimental Center “La Raya” (Cusco-Perú) showed that the protein content varied between 3.2% and 12.65%, indicating that the nutritional composition of high Andean grasses fluctuates depending on environmental factors such as rainfall and temperature in the region. On average, it had been reported a 20-g increase in plant protein during the rainy season compared to the dry season; moreover, the rainy season showed for *S. brachiphylla* and *S. mucronata* DOM (34.60% and 32.95%) and ME (4.45 and 4.15 MJ/kg) values close to *S. ichu* from the present

investigation (Chino Velasquez et al., 2022). Mixed livestock farming increases product diversification, and mixed grazing systems involving cattle can benefit biodiversity, soil carbon accumulation, and plant community structure (Su et al., 2023). Nevertheless, grazing condition assessment suggests that stocking rate ($\text{AU ha}^{-1} \text{ year}^{-1}$) should be adjusted for sustainable management of soils, vegetation, and ecosystem services; for example, the replacement of palatable plant species with non-palatable ones in areas with high alpaca concentrations highlights the negative impact of domestic camelids on vegetation composition (Muñoz et al., 2015). A study in the grassland regions of Uruguay mentioned the redesign of mixed livestock farming systems, a low sheep-to-cattle ratio, to reduce competition between sheep and cattle for grazing, enhancing the cattle energy balance, increasing the cow pregnancy rates, a key variable for the income of cow-calf farmers (Modernel et al., 2019).

Some authors observed a substantial decline in the dominant perennial tall grass functional group (highly palatable) with increasing grazing intensity; instead, there was an increase in the perennial short grass functional group (Zainelabdeen et al., 2020). However, among key species, *Stipa* stands out as a prevalent genus within the wet Puna ecosystem, *S. ichu* being primarily a non-forage plant; even so, South American camelids consume it, and cattle can even ingest it due to its fiber contribution to their diets (Briones Chuquilin & Estrada Zelada, 2018). *C. vicunarium* is another notable grass but has a lesser forage value compared to species within the *Festuca* genus (Edson et al., 2023). The genus *Festuca* comprises over 500 perennial grass species that are distributed worldwide; *F. dolichophylla* is primarily a food source for South American camelids such as llamas (*L. glama*) and alpacas (*V. pacos*; Eduardo-Palomino et al., 2024). Similarly, *F. rigescens*, an indigenous plant of South America, also holds nutritional value for both bovine and ovine livestock (Rojo et al., 2019). The literature indicates that cattle potentially cause more significant damage than alpacas and sheep due to higher forage consumption per animal and the weight of their hooves (Maldonado Fonkén, 2014). Another aspect to highlight is the higher greenhouse gas emissions per unit of product in extensive production systems, which rely on natural grasslands and often have low productivity due to the limited availability and poor quality of feed, that would be greater in the case of alpacas compared to sheep (Oquendo et al., 2022). Therefore, the impact varies depending on the type and number of livestock and external stressors such as climate and community management as a whole. From this perspective, the relationship between soil nutrients and vegetation composition is essential for grassland productivity.

The concentrations of calcium, phosphorus, potassium, and magnesium are closely linked to the activity of various enzymes in the blood serum of sheep within high Andean micro-basins; in a study, elevated levels of alkaline phosphatase indicated several physiological or pathological conditions; it had been reported during periods of dietary calcium deficiency, which may disrupt the calcium-to-phosphorus ratio and lead to health issues in animals exposed to fluctuating pasture or grassland quality (Grijalva Olmedo et al., 2025). Also, Gao et al. (2019) emphasized the importance of phosphorus in the plant life

cycle, noting its role in enhancing the resilience and adaptability of grassland species.

Nevertheless, only *C. vicunarium* appeared to exhibit an acceptable foliar phosphorus; the other three species showed considerably low levels in their foliage, which may be attributed to ecological strategies developed by these species to survive in nutrient-poor environments and potential nutrient competition resulting from the coexistence of multiple species. Additional limitations include factors such as water availability or deficiencies in other nutrients; for example, nitrogen deficiency may underlie the limited response to phosphorus present in soil (Cardozo et al., 2024).

Crude protein content in grass species is a key indicator of their nutritional quality, particularly in high Andean ecosystems where nutrient availability is limited and climatic conditions constrain plant growth; however, grazing or mowing in these areas can enhance both productivity and forage quality (Mayel et al., 2021). High variability among species was observed: *C. vicunarium* exhibited a significantly higher crude protein content ($8.23\% \pm 0.89\%$), indicating better forage quality. This value may reflect greater efficiency in nitrogen uptake or assimilation or possibly a positive influence of soil conditions or management practices.

In contrast, *F. dolichophylla* ($3.81\% \pm 0.42\%$) and *S. ichu* ($3.35\% \pm 0.98\%$) presented the lowest protein levels, indicating poor nutritional value. These values are characteristic of species adapted to nutrient-poor soils, with conservative resource-use strategies or that are in more advanced stages of phenological maturity. *F. rigescens* showed an intermediate protein content ($4.44\% \pm 0.74\%$), although it remains limiting for animal production (Ustariz et al., 2019). These differences may be linked to divergent functional strategies: Whereas *C. vicunarium* appears to follow a more productive, fast-growing strategy, the other species exhibit adaptations to more restrictive environments, favoring persistence over productivity.

Furthermore, when these values are compared with metabolizable energy (ME) data, *C. vicunarium* not only has the highest protein content but also the highest ME value (8.16 MJ/kg), confirming its superior value as a forage resource in high Andean ecosystems. In contrast, *S. ichu* had the lowest values for both protein and ME (6.29 MJ/kg), limiting its usefulness as forage in the absence of proper management or supplementation.

Sites with high protein content may be characterized by younger, less structurally developed forage. In contrast, areas with greater biomass and carbon accumulation tend to produce more voluminous forage, albeit of lower nutritional quality. As grasses mature, they accumulate biomass (\uparrow DryBio), lignin, and carbon (\uparrow CC); whereas digestibility (DOM) may increase, protein content typically declines. In other words, younger grasses tend to be richer in protein but have lower overall biomass. Protein content often correlates with plant phosphorus and is typically associated with sites offering higher forage quality. This pattern indicates that site differences are not solely determined by biomass quantity but also by the plants' capacity to absorb and accumulate essential nutrients, which directly influence the value of forage as a resource for livestock production.

C. vicunarium presented a C/N ratio of approximately 40, which is considered acceptable for native grasses and markedly superior to the other species. The remaining species exhibited C/N ratios exceeding 70–90, which suggests a high proportion of structural tissues, potentially lower palatability and forage quality, and slower decomposition rates if considered as inputs to soil organic matter. Thus, *C. vicunarium* stands out for having the most favorable C/N ratio, indicating superior nutritional value and greater potential as a forage resource.

Finally, the RDA indicated that variation in plant functional traits was closely associated with chemical and physical gradients, suggesting that both nutrient availability and site-related constraints play an important role in shaping productivity and forage quality across the study area, with potential implications for pasture management and soil conservation strategies.

5 | CONCLUSIONS

The carrying capacity assessment indicated that the current grazing pressure exceeded the recommended threshold. No detrimental effect was observed in soil carbon by the animal units, continuous or rotation grazing. However, significant differences between grazing grassland sites were observed in soil fertility, carbon storage, and plant nutritional quality. Soil carbon levels were elevated across all sites, but higher concentrations were observed at San Pedro de Cajas. *C. vicunarium* was the best option for animal nutrition, supported by C/N ratio, plant phosphorus, protein, DOM, and ME. The RDA indicated that plant functional traits are structured by chemical and physical gradients, highlighting the joint influence of nutrient availability and site constraints on productivity and forage quality. It is relevant to conduct more in-depth studies to evaluate the long-term impact, and the disparities highlight the importance of considering the unique characteristics of each grassland community when developing stocking and conservation management strategies. To improve knowledge of grazing impacts, future work should connect soil and forage quality with animal physiological responses.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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