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Original Article

Evaluation of nutrient extraction and uptake by forage grasses under high Andean mountain conditions in Peru

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Abstract

This study evaluated nutrient extraction and uptake in native forage grasses (*Festuca dolichophylla* and *Calamagrostis chrysantha*) and improved species (*Lolium perenne* and *Dactylis glomerata*) at 4,100 m a.s.l. in the Peruvian Andes using a completely randomized design. Results revealed significant interspecific variability in nutrient accumulation. *Dactylis glomerata* showed superior macronutrient accumulation, particularly Mg, while *Lolium perenne* achieved highest K extraction (0.07 t ha^{-1}) and biomass production. Native species demonstrated lower nutritional demands: *Festuca dolichophylla* reached maximum dry matter production (6 t ha^{-1}), while *Calamagrostis chrysantha* showed elevated Ca and P concentrations. Correlation analysis revealed strong positive associations among Ca, Mg, Cu, Fe, Mn, and Zn (r = 0.7-1.0), indicating coordinated uptake mechanisms. Nickel exhibited negative correlations with P (r = -0.6) and K (r = -0.5). Improved species require intensive fertilization, while native species offer sustainable alternatives for low-input high-altitude systems.

Keywords: Forage grasses, Nutrient uptake, Mountain grasslands, Soil fertilization

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Introduction

Andean livestock systems support rural livelihoods in Peru's highlands, where approximately 87% of the country's 824,000 agricultural producers are concentrated (MIDAGRI, 2017). However, mounting pressure on natural grasslands driven by overgrazing and land-use change (Rolando et al., 2017; Vásquez et al., 2023) promotes degradation with loss of vegetative cover and forage quality, especially during dry seasons (Paredes et al., 2014).

While natural rangelands are the main feed base in the puna, they often present seasonal shortages and limited nutritional quality (Flores et al., 2005). This has led to adoption of improved forages such as ryegrass (*Lolium perenne*) and orchardgrass (*Dactylis glomerata*), which can increase yield and nutritive value under high Andean conditions (Capstaff and Miller, 2018). Optimal pasture performance emerges from plant-environment interactions, with soil fertility being pivotal (Havlin and Heiniger, 2020).

Designing effective fertilization programs requires quantifying species-specific nutrient demand through foliar analyses paired with biomass measurements (Chica-Toro and Herrera, 2020). However**,** nutrient uptake information for High-Andean forage systems remains critically scarce, limiting the design of fertilization programs tailored to extreme altitude conditions. This knowledge gap is particularly significant given that effective fertilization can increase crude protein, digestibility, and biomass production, supporting higher livestock productivity and economic benefits for producers (Gislon et al., 2020).

Therefore, this study quantified nutrient extraction and uptake in native grasses (*Festuca dolichophylla*, *Calamagrostis chrysantha*) and improved species (*Lolium perenne*, *Dactylis glomerata*) under high Andean conditions (4,100 m a.s.l.) in Peru to develop species-specific fertilization strategies that improve nutrient-use efficiency and sustain pastoral systems in extreme altitude environments.

This study aimed to: (1) quantify nutrient extraction and uptake patterns in native and improved forage species at 4,100 m a.s.l., (2) identify nutrient correlation patterns and coordinated uptake mechanisms, and (3) determine species-specific fertilization requirements for developing sustainable high-altitude pasture management strategies in the central Peruvian Andes.

Material and Methods

Study site

The study was conducted in natural puna grasslands located in Ninacaca District, Pasco Province, Pasco Department, central Peru, at an elevation of 4,100 m above sea level (10.864620° S, 76.137135° W; see Figure 1). The site falls within the very humid subalpine tropical páramo life zone (INRENA, 1995). Climate is markedly seasonal: the rainy period is characterized by temperatures ranging from −3.8 °C to 16.8 °C, while the dry period ranges from −11.8 °C to 16.4 °C. Mean relative humidity is 79.6%, and mean annual precipitation totals 821.3 mm, based on records from the Junín meteorological station (SENAMHI, 2025).

Soils across the hills and mountains are classified as dystric Leptosol–vitric Andosol (LPd–ANz), with smaller proportions of sloping ridges supporting low-quality pastures (ANA et al., 2015; SIGMINAM, 2010). Soil profiles are typically AC or BC, with predominantly sandy loam textures and pH values between 6 and 7 (INRENA, 1996). At the experimental site specifically, soils were slightly alkaline (pH 7.5), with very high organic matter content (18.1%), low available phosphorus (4.6 mg/kg), low potassium (96.7 mg/kg), and a sandy loam texture (Sales-Dávila et al., 2024). Vegetation is dominated by grasslands, principally communities of *Festuca*, *Jarava* and *Calamagrostis* (Arias-Arredondo et al., 2025).

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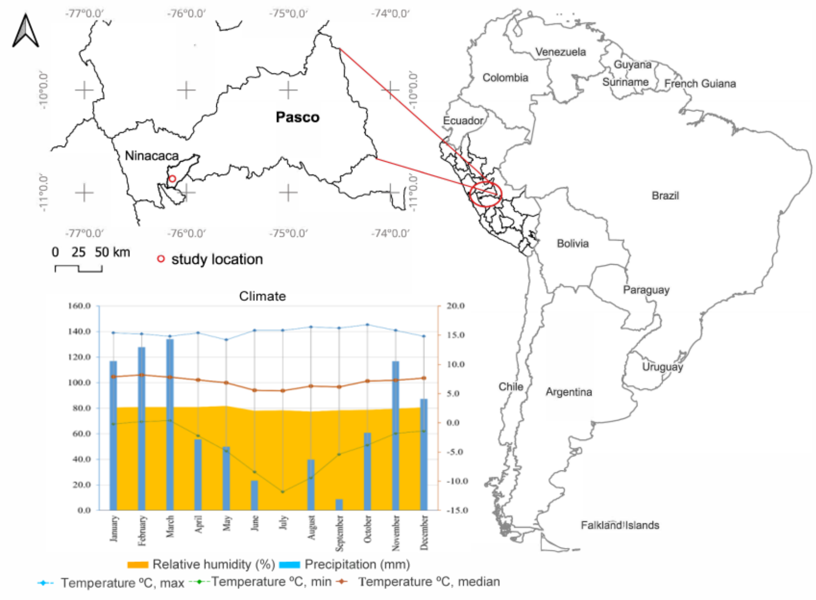

Figure-1. Study location and climatic conditions of the experimental site. The map shows the research site in Ninacaca, Pasco Region, central Peruvian Andes (4,100 m a.s.l.).
The climate diagram displays monthly precipitation (mm), relative humidity (%), and maximum, minimum and median temperatures (°C).

Plants for measurement and experimental design

The experiment followed a completely randomized design with four treatments (species) and three replicates per treatment, yielding 12 experimental units in total. Four forage grass species were evaluated: two native to high Andean grasslands (*Festuca dolichophylla* and *Calamagrostis chrysantha*) and two improved cultivated species (*Lolium perenne* and *Dactylis glomerata*). Each experimental unit consisted of a 1 m × 1 m monoculture plot established with a single grass species. Prior to transplantation, all species were taxonomically identified using specialized botanical keys for Andean grasses and confirmed by plant taxonomy specialists.

Plant sampling was conducted eight months after transplantation, during the late vegetative stage and prior to the onset of flowering. This phenological window was selected to capture peak vegetative biomass accumulation and active nutrient uptake, before nutrient translocation to reproductive organs occurs.

Nutrient analysis

Tissue samples were collected from the aerial parts of the species studied (*Festuca dolichophylla*, *Calamagrostis chrysantha*, *Lolium perenne* and *Dactylis glomerata*), which were dried at 65 °C until constant weight and then finely ground. The analyses were carried out at the Soil, Water, and Foliar Laboratory (LABSAF) of the Santa Ana experimental station of the National Institute of Agricultural Innovation (INIA). Phosphorus (P, %) was determined using the AS-10 method following the procedure of Olsen and Sommers (1982), and potassium (K, %) using the AS-12 method with ammonium acetate extraction (Semarnat, 2002; Sales-Dávila et al., 2024). The nutrients Ca, Mg, Cu, Fe, Mn, Mo, Ni, and Zn (mg kg^{-1}) were determined by microwave-assisted acid digestion, followed by atomic absorption spectroscopy (Salome Araujo et al., 2020; Sarmiento Gamero et al., 2021). The equipment was calibrated using certified standard solutions at multiple concentration levels, with correlation coefficients (R^2) greater than 0.999. Quality control included the analysis of blanks, duplicate samples, and certified reference materials to ensure analytical accuracy and precision. Recoveries were within the range of 95–105%, with relative standard deviations below 5%. Detection and quantification limits were estimated as three and ten times the standard deviation of the blanks, respectively.

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Biomass production

Biomass production was measured using 1 m^2 quadrats placed within the central area of each experimental plot, maintaining a minimum distance of 0.5 m from plot edges to eliminate border effects (Arias A et al., 2021; Bartl et al., 2009). Quadrat placement was randomized using generated coordinates within the effective sampling area, ensuring representative sampling free from marginal interference. Plants within each quadrat were cut at ground level, then bagged, labeled, and weighed to determine fresh matter (FM), expressed in t ha^{-1}. Samples were subsequently oven-dried at 60 °C for 48 hours to determine dry matter (DM) weight, also expressed in t ha^{-1}. Dry matter percentage (DM%) was calculated using Equation 1:

$$\mathbf{DM\% = (P\mathit{f} / P\mathit{i}) \times 100 \qquad (1)}$$

where P*f* is the final (dry) weight and P*i* is the initial (fresh) weight.

Nutrient uptake

Macronutrient concentrations (P, K, Ca, and Mg) and micronutrient concentrations (Cu, Fe, Mn, Mo, Ni, and Zn) in plant tissue were used to calculate nutrient extraction using Equation 2 (Martínez-Gutiérrez et al., 2022):

$$\mathbf{NE = (DM \times NC) / 100 \qquad (2)}$$

where NE is nutrient extraction (t ha^{-1} for macronutrients; kg ha^{-1} for micronutrients), DM is the dry matter of the plant organ (t ha^{-1}), and NC is the nutrient concentration in dry matter (% for macronutrients; mg kg^{-1} for micronutrients). The NE values obtained from Equation 2 were then used to express nutrient extraction in fertilizer oxide equivalents (P_2O_5, K_2O, CaO, and MgO) using Equation 3:

$$\mathbf{FC = NE \times F \times 1000 \qquad (3)}$$

where FC is fertilizer uptake (kg ha^{-1}) and F is the conversion factor to oxide form. To support fertilization planning on a per-unit-production basis, the fertilization dose was estimated by combining the terms from Equations 2 and 3 into Equation 4 (Navarro García and Navarro García, 2023):

$$\mathbf{FD = ((DM \times NC) / 100 \times F) \times 1000 \qquad (4)}$$

where FD is the fertilization dose (kg ha^{-1}), and DM, NC, and F are as defined above.

Statistical analysis

All statistical analyses were based on parametric methods, following verification of the assumptions of normality and homogeneity of variance. A one-way analysis of variance (ANOVA) was performed to test for significant differences among treatments, followed by Fisher's least significant difference (LSD) post hoc test ($\alpha = 0.05$) to identify pairwise differences between means. Bivariate relationships among variables were assessed using Pearson's correlation coefficient, with results presented as a correlation matrix displaying the direction and magnitude of associations. All analyses were conducted in R (Version 4.0.2; R Core Team, 2020).

Results

Foliar nutrient concentrations

Significant interspecific variability was observed in foliar nutrient concentrations across the four grass species ($p < 0.05$; Figure 2; Supplementary Table S1). *Dactylis glomerata* recorded the highest concentrations of Ca (2.7%), Cu (21.9 mg kg^{-1}), Fe (4,134 mg kg^{-1}), Mg (0.46%), Mn (170.9 mg kg^{-1}), Mo (1 mg kg^{-1}), P (0.29%), and Zn (77.4 mg kg^{-1}), differing significantly from the remaining species. *Lolium perenne* showed the highest K concentration (1.4%) and intermediate values for most other nutrients. Among the native species, *Calamagrostis chrysantha* exhibited moderate concentrations of Ca (2.1%) and P (0.20%), whereas *Festuca dolichophylla* recorded the lowest concentrations for the majority of nutrients evaluated, including Cu (10.7 mg kg^{-1}), Fe (658.4 mg kg^{-1}), and Zn (47.9 mg kg^{-1}). Ni was the only nutrient for which the improved species did not rank highest; concentrations were greatest in *Calamagrostis chrysantha* (9.95 mg kg^{-1}) and lowest in *Dactylis glomerata* (3.84 mg kg^{-1}), though this difference was not statistically significant.

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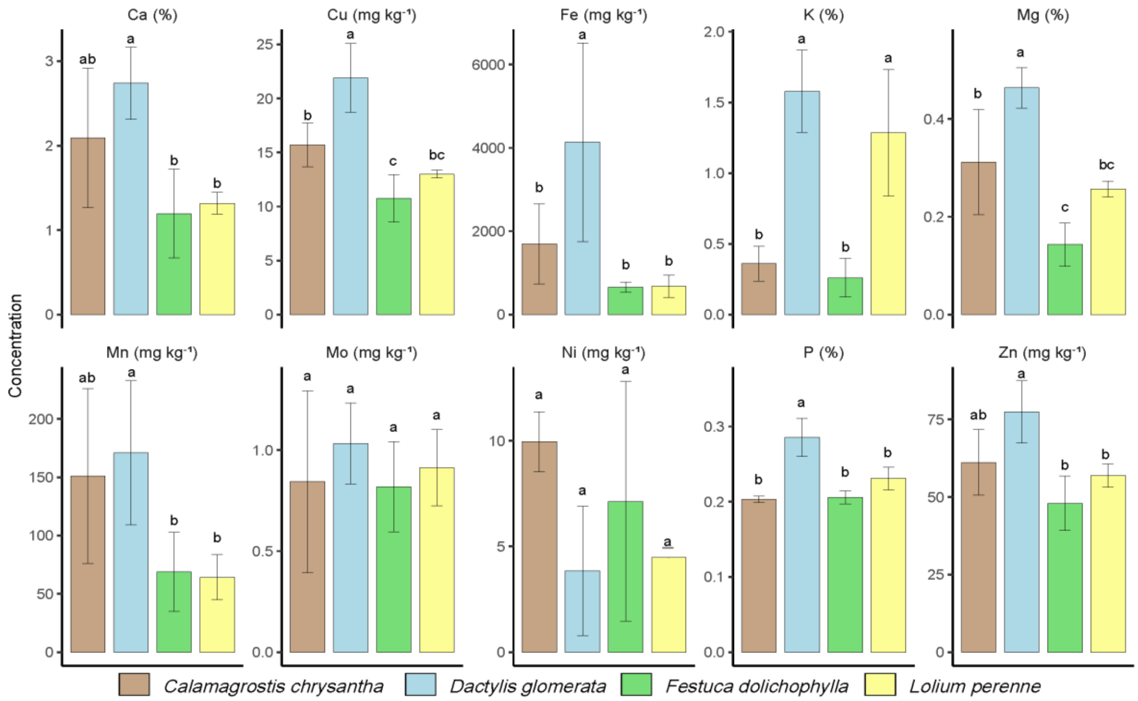

Figure-2. Foliar macro- and micronutrient concentrations in four high Andean forage grass species (4,100 m a.s.l.).
Bars represent mean ± standard error. Different letters indicate statistically significant differences among species ($p < 0.05$).

Pearson correlation analysis revealed distinct patterns of nutrient association among the species evaluated (Figure 3). A primary cluster of positive intercorrelations was identified among Ca, Mg, Cu, Fe, Mn, and Zn (r = 0.5–1.0), with the strongest relationships observed between Cu and Zn (r = 1.0), Mg and Ca (r = 0.9), Cu and Mg (r = 0.9), and Mg and Zn (r = 0.9). Phosphorus showed moderate positive correlations with K (r = 0.8) and with the primary cation cluster (r = 0.6–0.8). In contrast, Ni exhibited negative correlations with P (r = −0.6) and K (r = −0.5), suggesting potential antagonism or competition at absorption sites. Mo showed weak correlations with most nutrients, while Mn displayed moderate positive associations with the primary cation cluster (r = 0.6–0.9). Hierarchical clustering confirmed these patterns, yielding three distinct groupings: a primary cluster of highly intercorrelated nutrients (Ca, Mg, Cu, Zn, Fe, and Mn); a secondary cluster in which P and K grouped together before merging with the primary cluster; and isolated positions for Ni and Mo, reflecting their largely independent or antagonistic relationships with the remaining nutrients.

Biomass production and quality parameters

Significant interspecific variation was observed in all biomass production and quality parameters ($p < 0.05$; Figure 4; Supplementary Table S2). *Festuca dolichophylla* achieved the highest dry matter yield (6.1 t ha⁻¹), differing significantly from *Dactylis glomerata* (3.3 t ha⁻¹), while *Calamagrostis chrysantha* (4.1 t ha⁻¹) and *Lolium perenne* (5.1 t ha⁻¹) showed intermediate values. Moisture content was highest in *Lolium perenne* (58%), whereas the remaining species showed similar values (37–39%). Fresh matter yield was greatest in *Lolium perenne* (12.9 t ha⁻¹), followed by *Festuca dolichophylla* (10 t ha⁻¹), with *Calamagrostis chrysantha* and *Dactylis glomerata* recording the lowest values (5–7 t ha⁻¹). Dry matter percentage was consistently high in *Calamagrostis chrysantha*, *Dactylis glomerata*, and *Festuca dolichophylla* (60–62%), while *Lolium perenne* showed significantly lower values (41%). Overall, these results suggest that native species, particularly *F. dolichophylla*, demonstrate superior dry matter accumulation efficiency under high-altitude Andean conditions, while *L. perenne* showed higher moisture retention and fresh matter yield despite lower dry matter content.

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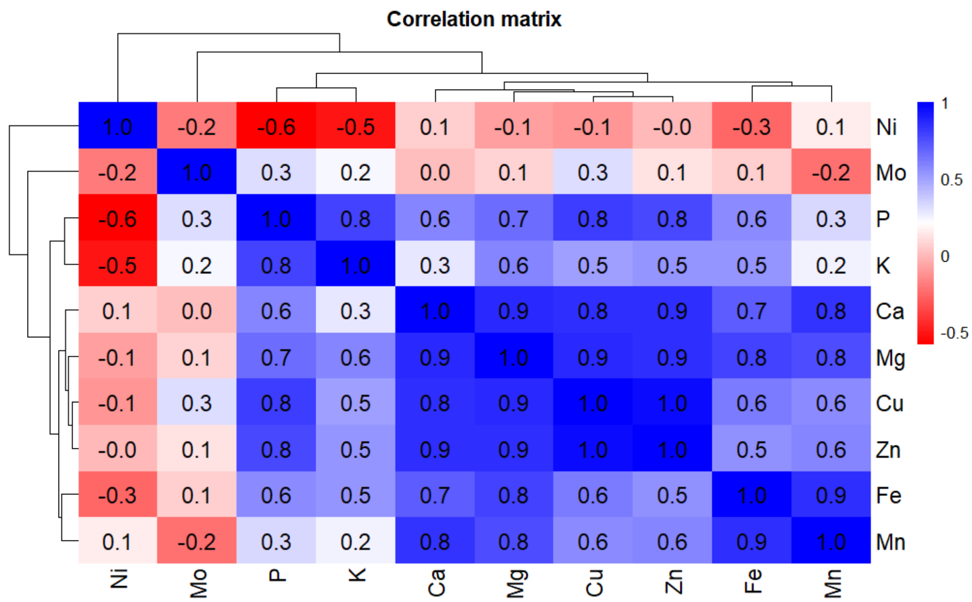

Figure-3. Pearson correlation matrix of macro and micronutrient concentrations in leaf tissue of four high Andean forage grass species.
Color intensity indicates the strength of the correlation, with blue representing positive and red representing negative associations. The dendrogram illustrates hierarchical clustering of nutrients based on correlation patterns.

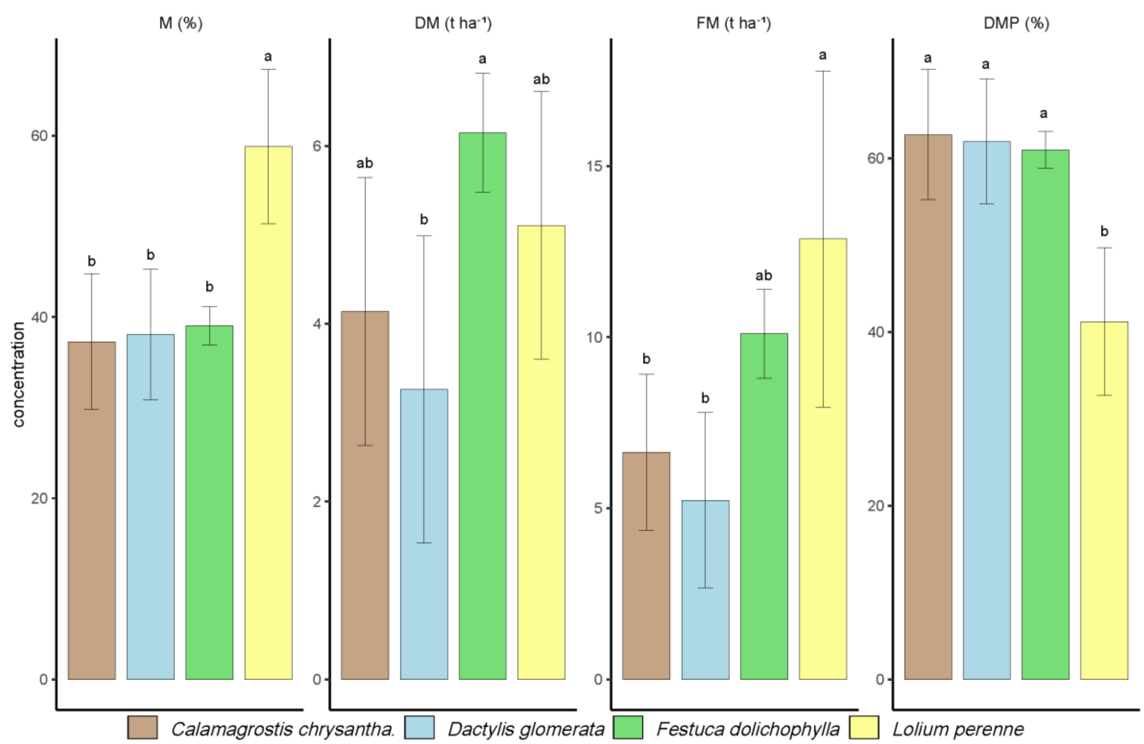

Figure-4. Biomass production and quality parameters of four high Andean forage grass species.
M: moisture content (%); DM: dry matter yield (t ha^{-1}); FM: fresh matter yield (t ha^{-1}); DMP: dry matter percentage (%).
Bars represent mean ± standard error. Different letters indicate statistically significant differences among species ($p < 0.05$).

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Nutrient extraction

Significant interspecific differences were observed in nutrient extraction per unit area ($p < 0.05$; Figure 5; Supplementary Table S3). *Lolium perenne* demonstrated the highest K extraction (0.07 t ha^{-1}), significantly exceeding *Calamagrostis chrysantha* and *Dactylis glomerata* (0.01–0.05 t ha^{-1}). Among micronutrients, *Dactylis glomerata* showed the highest Fe extraction (~16 kg ha^{-1}), while in Cu and Zn extraction, all species had values ranging from 0.063 to 0.068 and 0.24 to 0.29 (kg ha^{-1}), and *Calamagrostis chrysantha* achieved the highest Mn extraction (0.624 kg ha^{-1}). Calcium extraction was relatively uniform across species (0.07–0.09 t ha^{-1}), with no significant differences detected. Magnesium extraction was highest in *Dactylis glomerata* (0.02 t ha^{-1}) compared to the native species (0.01 t ha^{-1}). Phosphorus extraction remained low and similar across all species (0.008–0.01 t ha^{-1}). Mo and Ni showed minimal extraction rates (< 0.05 kg ha^{-1}) across all species. Collectively, these patterns suggest differential nutrient use efficiency strategies between native and introduced forage species, potentially reflecting distinct ecological adaptations in nutrient cycling under high-altitude Andean conditions.

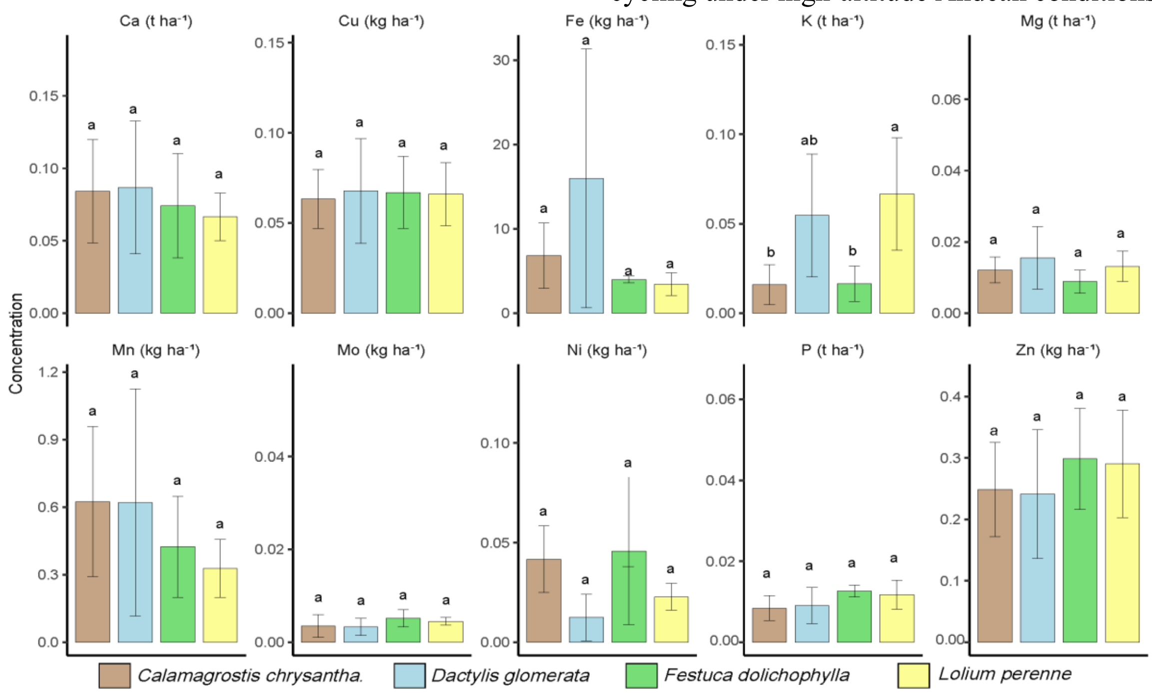

Figure-5. Nutrient extraction capacity of four high Andean forage grass species.
Bars represent mean ± standard error. Different letters indicate statistically significant differences among species ($p < 0.05$).

Correlation between nutrient extraction and biomass parameters

The correlation matrix revealed complex but structured relationships among nutrient extraction and biomass production variables (Figure 6). Within the primary nutrient cluster, strong positive correlations were observed among Ca, Mg, and Mn, with Ca–Mg (r = 0.8), Ca–Mn (r = 0.9), and Mg–Mn (r = 0.9) indicating coordinated extraction patterns. Biomass production parameters were significantly associated with nutrient uptake: DM showed strong positive correlations with Zn (r = 0.9), Mo (r = 0.8), P (r = 0.8), and Cu (r = 0.7), suggesting that greater biomass accumulation is associated with enhanced extraction efficiency for these nutrients. FM exhibited moderate to strong positive correlations with most nutrients (r = 0.5–0.8), following a similar pattern to DM. In contrast, moisture content (M) showed strong negative correlations with DMP (r = −1.0) and with several nutrients, reflecting the inverse relationship between water content and nutrient concentration on a dry weight basis. Ni extraction showed weak associations with most parameters, while K showed moderate correlations with biomass variables (r = 0.4–0.5). Overall, these patterns indicate that biomass production is closely linked to nutrient extraction capacity in high-altitude forage systems.

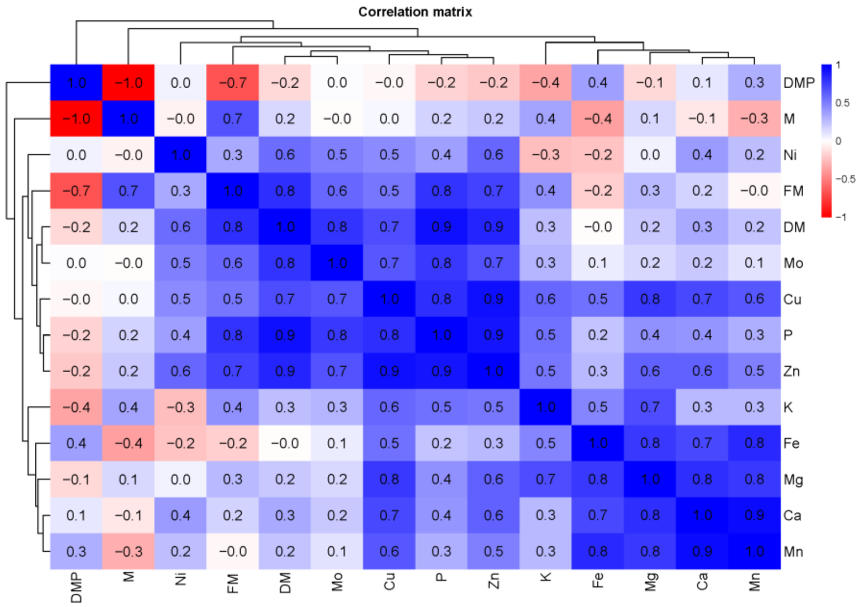

Figure-6. Pearson correlation matrix of nutrient extraction and biomass production parameters in four high Andean forage grass species.

Color intensity indicates the strength of the correlation, with blue representing positive and red representing negative associations. DM: dry matter yield; FM: fresh matter yield; M: moisture content; DMP: dry matter percentage. The dendrogram illustrates hierarchical clustering based on correlation patterns.

Nutrient uptake in fertilizer equivalent form

Significant interspecific variation was observed in nutrient uptake expressed as fertilizer equivalents ($p < 0.05$; Figure 7; Supplementary Table S4). Among the introduced species, *Dactylis glomerata* recorded the highest Fe extraction (~16,000 g ha^{-1}), while *Lolium perenne* showed the greatest K_2O uptake (80 kg ha^{-1}), differing significantly from the native species. CaO and MgO extraction were relatively uniform across species (~90–122 kg ha^{-1} and ~14–26 kg ha^{-1}, respectively), with no significant differences detected. Among the native species, *Festuca dolichophylla* achieved the highest P_2O_5 extraction (29 kg ha^{-1}) and competitive Zn uptake (~300 g ha^{-1}), while *Calamagrostis chrysantha* showed the greatest Mn extraction (~600 g ha^{-1}). Cu uptake was similar across all species (60–70 g ha^{-1}), and Mo extraction remained consistently low (3–5 g ha^{-1}). Ni uptake was greater in the native species (*F. dolichophylla*: 45 g ha^{-1}; *C. chrysantha*: 41 g ha^{-1}) than in the introduced species (*D. glomerata*: 12 g ha^{-1}; *L. perenne*: 23 g ha^{-1}), though differences were not statistically significant. These results suggest differential fertilizer replacement values among species, with introduced grasses generally exhibiting higher extraction capacity for key macronutrients.

Fertilization requirements for a target production of 10 t ha^{-1}

Substantial interspecific differences were observed in estimated fertilization requirements to achieve a target production of 10 t ha^{-1} ($p < 0.05$; Figure 8; Supplementary Table S5). *Dactylis glomerata* showed the highest demands across most nutrients, requiring 383 kg ha^{-1} CaO, 220 g ha^{-1} Cu, 42,000 g ha^{-1} Fe, 190 kg ha^{-1} K_2O, 77 kg ha^{-1} MgO, 1,700 g ha^{-1} Mn, and 65 kg ha^{-1} P_2O_5, differing significantly from the other species. *Lolium perenne* showed moderate to high demands, particularly for K_2O (155 kg ha^{-1}) and MgO (43 kg ha^{-1}). Native species exhibited comparatively lower fertilization requirements: *Festuca dolichophylla* required 167 kg ha^{-1} CaO, 107 g ha^{-1} Cu, 6,600 g ha^{-1} Fe, and 24 kg ha^{-1} MgO, while *Calamagrostis chrysantha* showed intermediate demands for CaO (293 kg ha^{-1}) and Cu (157 g ha^{-1}). Mo requirements remained consistently low across all species (8–10 g ha^{-1}). Overall, these estimates indicate that native species offer meaningful advantages for low-input production systems under high-altitude Andean conditions.

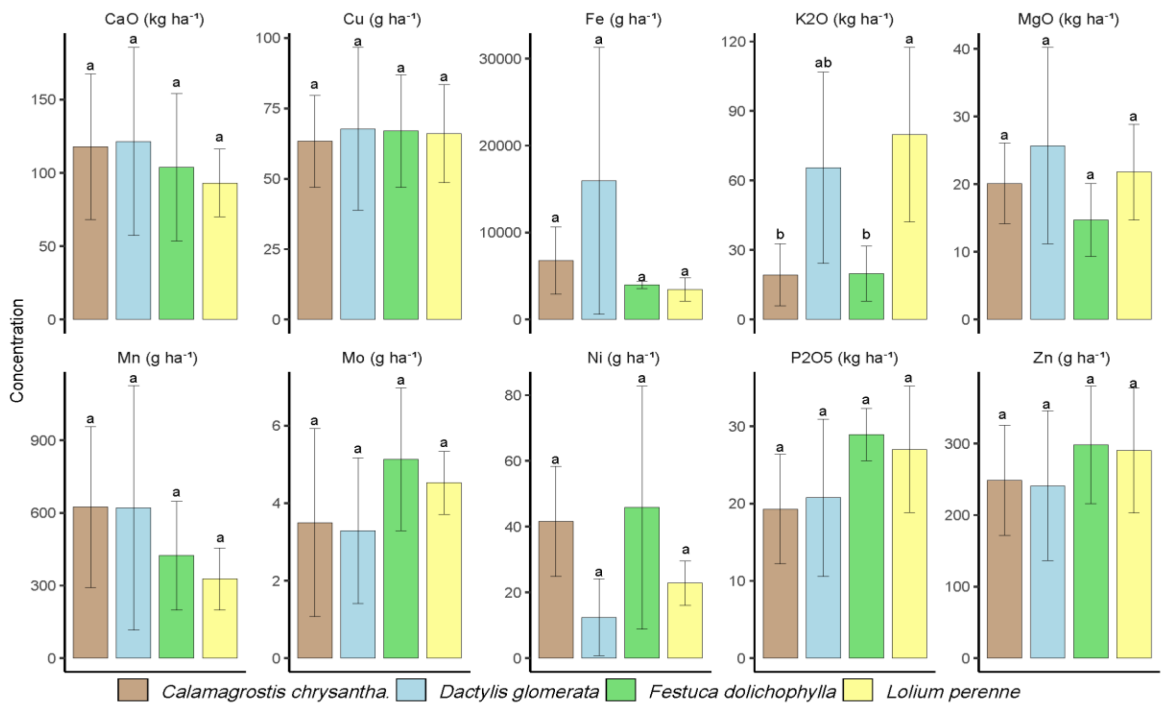

Figure-7. Nutrient uptake expressed as fertilizer equivalents in four high Andean forage grass species.
Bars represent mean ± standard error. Different letters indicate statistically significant differences among species ($p < 0.05$).

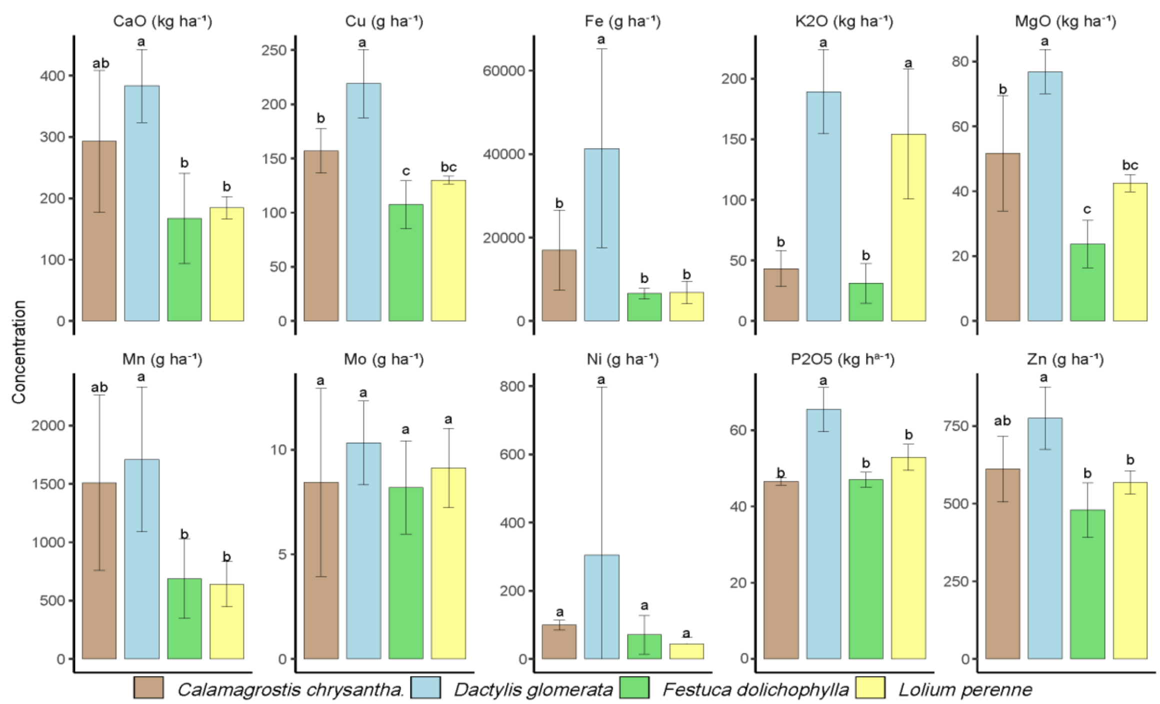

Figure-8. Estimated fertilization requirements to achieve a target forage production of 10 t ha^{-1} in four high Andean grass species.
Bars represent calculated nutrient demands ± standard error. Different letters indicate statistically significant differences among species ($p < 0.05$).

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Discussion

The results demonstrate marked interspecific variability in nutrient extraction and uptake capacity among the forage grasses evaluated, representing the first comprehensive assessment of this kind at 4,100 m a.s.l. in the central Peruvian Andes. At this extreme altitude, unique physiological constraints are likely to shape nutrient dynamics in ways that distinguish these findings from studies conducted at lower elevations.

The coordinated uptake patterns identified through correlation analysis particularly the Ca–Mg–Cu–Fe–Mn–Zn cluster ($r = 0.5–1.0$) suggest altitude-specific adaptations not previously documented in Andean forage systems. Of particular note is the antagonistic relationship between Ni and primary nutrients (P: $r = −0.6$; K: $r = −0.5$), which may reflect competitive transport mechanisms under conditions of environmental stress. These patterns contrast with those reported at lower altitudes, where such antagonisms tend to be less pronounced (Ustariz et al., 2019).

Dactylis glomerata exhibited the highest nutrient accumulation capacity across most elements but also the greatest fertilization demands (e.g., 380 kg ha^{-1} CaO equivalent), positioning it as suitable primarily for intensive production systems. In contrast, *Festuca dolichophylla* achieved the highest dry matter yield (6.0 t ha^{-1}) with comparatively low nutrient inputs, demonstrating notable resource use efficiency that had not previously been quantified under central Andean conditions. The approximately 2.5-fold difference in fertilization requirements between improved and native species represents a key finding with direct implications for the sustainability of high-altitude pastoral systems.

Biomass yields in the present study exceeded those reported for comparable altitudes in previous work (Mamani Paredes et al., 2024; Trillo Zárate et al., 2020), suggesting that controlled experimental conditions can unlock productive potential that is not typically realized in degraded natural grasslands. The positive correlation between biomass production and nutrient extraction efficiency further indicates that productive capacity and nutrient mobilization are functionally linked traits under high-altitude stress.

The estimated fertilization requirements for a target production of 10 t ha^{-1} reveal that improved species demand approximately three to five times the nutrient inputs of native species, raising important questions about the sustainability of intensive management approaches in resource-limited high-altitude communities. Native species, by contrast, offer viable alternatives for low-input systems while maintaining ecosystem services and contributing to pastoral resilience under climate uncertainty. In these environmentally constrained settings, species selection criteria should prioritize resource use efficiency over maximum productivity.

From a practical standpoint, native species (*F. dolichophylla* and *C. chrysantha*) require only approximately 25–50% of the calculated fertilization values for sustainable production, making them well suited to resource-limited producers. Improved species, however, approach optimal performance only under intensive management near 100% of calculated requirements. Fertilizer applications are recommended during the pre-rainy season (October–November) using locally available compound fertilizers, with native species offering additional economic advantages through reduced input costs.

Several limitations of this study should be acknowledged. The research was conducted at a single site, which may constrain the generalizability of findings across the diverse microclimatic and edaphic conditions characteristic of Andean ecosystems. The temporal scope was restricted to a single sampling event during the late vegetative stage, precluding assessment of seasonal nutrient dynamics or phenological variation across complete growth cycles. Furthermore, the absence of pre- and post-experiment soil nutrient data and root zone analyses limits the ability to quantify nutrient depletion rates or establish precise soil–plant nutrient balances. The controlled experimental conditions may also not fully capture the complex biotic and abiotic interactions present in natural or managed grassland systems. Future research should address these gaps through multi-site, multi-temporal studies incorporating comprehensive soil–plant interaction assessments, with the aim of producing more robust fertilization guidelines for diverse Andean pastoral systems.

Conclusions

The results of this study revealed significant interspecific variability in nutrient extraction capacity, biomass production, and fertilization requirements among four forage grass species evaluated under high-altitude Andean conditions. The improved species, *Dactylis glomerata* and *Lolium perenne*, exhibited greater nutrient uptake and biomass accumulation but

required substantially higher fertilization inputs, whereas the native species, *Festuca dolichophylla* and *Calamagrostis chrysantha*, showed lower nutritional demands alongside species-specific absorption patterns consistent with high-altitude adaptations.
Correlation analysis identified strong positive associations among Ca, Mg, Cu, Fe, Mn, and Zn, indicating coordinated synergistic accumulation, while Ni exhibited antagonistic relationships with P and K, suggesting competitive dynamics at absorption sites.
The differential fertilization requirements quantified in this study provide a basis for differentiated management strategies in Andean pastoral systems. Native species, requiring approximately 25–50% of the inputs demanded by improved species, represent suitable options for low-input and resource-limited production contexts. Improved species remain appropriate where productive intensity justifies higher nutrient investments and full fertilization programs can be sustained.
The complementary use of native and improved forage species offers a practical framework for enhancing livestock productivity while preserving biodiversity and maintaining soil health in high Andean grasslands. These findings contribute foundational knowledge for the development of sustainable forage management guidelines adapted to the ecological and socioeconomic constraints of high-altitude pastoral systems.

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Contribution of Authors
Arias-Arredondo A: Conceptualization, investigation, methodology, validation and writing – original draft.
Lopez-Rodriguez M: Methodology, validation and investigation.
Cruz-Luis J: Funding acquisition, investigation, resources and validation.
Requena-Rojas E: Validation, writing – review and editing.
Ccopi D: Software, validation, writing – review and editing.
Pizarro S: Software, supervision, validation, writing – review and editing.
Solórzano-Acosta R: Supervision, validation, writing – review and editing.

All authors read and approved the final draft of the manuscript.

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