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The response of medium and trace elements in degraded alpine meadow soils to vegetation characteristics and soil physicochemical properties

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Abstract: Alpine meadows, one of the most widespread and important vegetation types on the Qinghai-Tibet Plateau, are facing severe degradation. This study examines how degradation affects soil medium and trace elements in the eastern Qinghai-Tibet Plateau, along with their relationships with plant traits and soil properties. Results indicate that alpine meadow degradation significantly reduces vegetation coverage, height, biomass, soil water content (SWC), and the levels of soil organic carbon (SOC), nitrogen (N), and phosphorus (P), while increasing soil bulk density (BD), pH, and potassium (K) content. Soil Ca, Zn, and Mo decrease with degradation, whereas Mg, Fe, Mn, Cu, Ni, and Co increase, with Ca, Fe, and Mn showing the strongest changes. Correlation and redundancy analyses indicate that aboveground biomass, SWC, SOC, N, and P positively correlate with Ca, Mo, and Zn, while pH, BD, and K associate with Mn, Fe, Ni, Co, Mg, and Cu. Therefore, alpine meadow degradation significantly influences the distribution of certain soil physicochemical properties and medium and trace elements in the eastern Qinghai-Tibet Plateau. Meanwhile, these medium and trace elements are also affected by specific soil physicochemical properties. Future grassland restoration should consider not only macronutrients and basic soil properties but also key elements like Ca, Fe, and Mn. This study provides foundational data for the ecological restoration of degraded alpine meadows.

Keywords: meadow degradation; plant community characteristics; Qinghai-Tibet Plateau; soil element characteristics

The Zoige Plateau, located in the semi-humid region of the eastern Qinghai-Tibet Plateau. It is not only a vital component of the Qinghai-Tibet Plateau ecological barrier but also hosts the world's largest alpine peat swamp wetlands and represents one of China's key biodiversity hotspots, making its ecological position exceptionally significant (Xu et al. 2023; Shi et al. 2025). Characterised by high altitude and low temperatures, this region exhibits weak biogeochemical processes in soil formation, resulting in a sensitive and fragile ecosystem (Chen et al. 2023). In recent decades, global climate change and unsustainable anthropogenic activities have severely degraded the alpine meadow ecosystems in Zoige, posing serious challenges to regional economic and social development (Shi et al. 2025). Grassland degradation manifests superficially through reduced species richness, declining biodiversity, and decreased biomass (Zhang et al. 2025a), while soil degradation involves structural fragmentation, substantial nutri-

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ent loss, and functional deterioration, ultimately impairing plant growth and development (Luo et al. 2022). Therefore, investigating the impacts of grassland degradation on soil properties holds significant scientific and practical importance.

Vegetation degradation and soil degradation are direct manifestations of grassland degradation. Due to the distinct attributes of plants and soils, soil degradation in grassland systems often lags behind vegetation degradation but is more difficult to restore once degraded (Du et al. 2025). Numerous studies have demonstrated that the relationship between aboveground vegetation characteristics and soil environmental factors is crucial for understanding the connection between biodiversity and ecosystem functioning (Zhang et al. 2025b). Plant nutrients include macronutrients such as nitrogen, phosphorus, and potassium, as well as medium and trace elements like calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), boron (B), and molybdenum (Mo). Beyond macronutrients, medium and trace elements in soil are essential for normal plant growth and development. The deficiency of these elements can cause nutrient deficiency symptoms in plants, while their excess may lead to soil compaction and antagonism (e.g., between Ca^{2+}/Mg^{2+} ions and other nutrients), which impairs nutrient uptake. Additionally, excess may result in heavy metal toxicity (from Fe, Mn, Cu, Zn, etc.), ultimately harming plant growth and even posing a threat to human and animal health (Mu et al. 2023). For instance, Fe is involved in chlorophyll biosynthesis and stabilisation, serving as a component of respiratory and photosynthetic electron transport systems and as a cofactor for electron carriers (Cyt f, Cyt b559, and Cyt b563), closely associated with CO_2 fixation. Fe deficiency leads to stunted growth and reduced rhizobium activity and nitrogen fixation in legumes (Rai et al. 2021). Mn deficiency inhibits photosynthesis, reducing photosynthetic products and dry matter accumulation (Heine et al. 2011). Cu deficiency causes slow growth, dwarfism, chlorosis, necrosis, and reduced seed set (Zhu et al. 2012). Recent studies on medium and trace elements in grassland soils have increased. Hu and Zhou (2024) found that long-term grazing exclusion in Inner Mongolia's semi-arid grasslands enhanced plant uptake of trace elements, reducing their soil concentrations. Qi et al. (2024) observed that in Qilian Mountain's semi-arid grasslands, soil Zn, Mn, and Ca decreased with degradation severity, while Se, Fe, Mg, Mo, Cu, and Co increased.

Current research on soil properties of alpine meadows in the semi-humid region of the eastern Qinghai-Tibet Plateau primarily focuses on soil structure, conventional physicochemical properties, and stoichiometric analysis (Li et al. 2024; Zhang et al. 2024), while studies on medium and trace element variations in degraded alpine meadow soils of this region remain scarce. This study, therefore, investigates the characteristic changes of medium and trace elements during alpine meadow degradation in the semi-humid eastern Qinghai-Tibet Plateau, analysing their relationships with plant biomass and soil physicochemical properties. The findings aim to provide references for formulating restoration strategies.

MATERIAL AND METHODS

Study site and land history. This study selected the Zoige National Nature Reserve (33°55'–33°56'N, 102°49'–102°50'E) (Figure 1) in the eastern Qinghai-Tibet Plateau as the research area, with an average altitude of 3 500 m. The region features a typical continental plateau cold-temperate semi-humid monsoon climate, with a mean annual temperature of 1.7 °C and annual precipitation ranging from 600–700 mm. The reserve exhibits gentle terrain with well-developed meandering rivers and dense marshes, containing numerous waterways but relatively homogeneous vegetation types. The dominant vegetation consists of meadow plant communities dominated by *Kobresia tibetica* and *Blysmus sinocompressus*, with soils developing from alluvial deposits mixed with minor slope wash and diluvial parent materials to form meadow soils. Over recent decades, under combined natural and anthropogenic influences, the area has experienced varying degrees of degradation and even desertification, severely constraining regional economic and ecological sustainable development (Luo et al. 2022; Qian et al. 2024).

Soil sampling and parameter analysis. In August 2021, based on consistent parent material and topographic conditions, and referring to previous research (Zhang et al. 2024; Liu et al. 2025) and field survey data (coverage, height, dominant plant species, and rodent hole density), the alpine meadows were classified into native meadow (NM), lightly degraded meadow (LDM), moderately degraded meadow (MDM), and heavily degraded meadow (HDM) (Table 1). Three 50 × 50 m plots were established for each meadow type (totalling 12 plots). The distance between each

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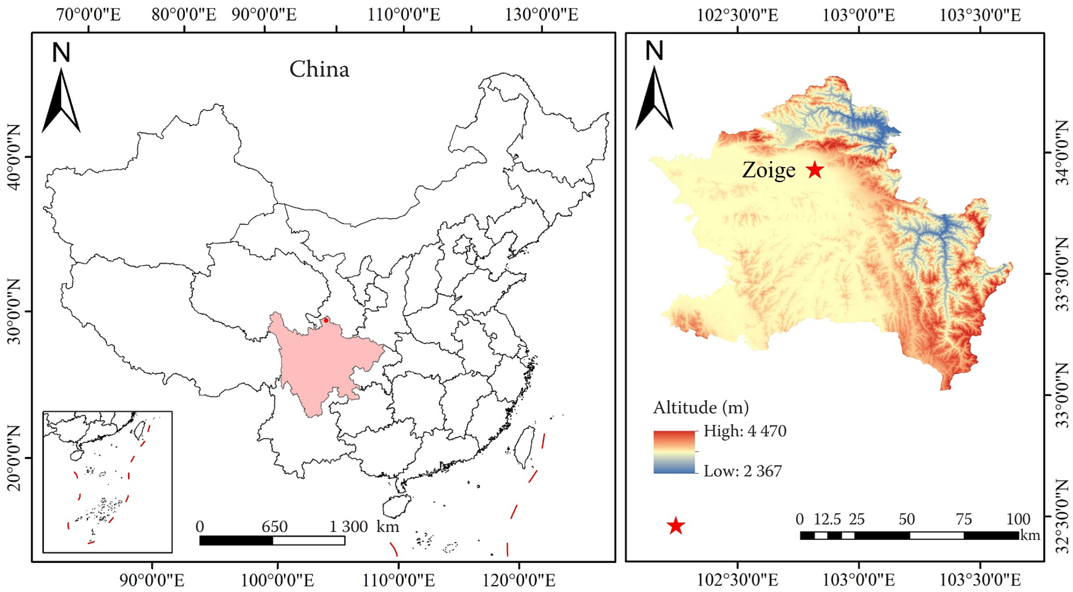

Figure 1. Study area

sample plot is greater than 100 m. Within each plot, three 1 × 1 m quadrats were randomly placed to survey vegetation coverage and height. All aboveground plants within the quadrats were clipped, collected in sealed plastic bags. One intact soil block (20 × 20 cm) with roots was excavated for belowground root biomass determination. Undisturbed soil samples were collected using 100 cm^3 cutting rings for bulk density analysis. Soil samples from 0–20 cm depth were collected, with three quadrat samples from the same plot thoroughly mixed and quartered to obtain 2 kg composite samples. These were stored in sealed bags, air-dried, sieved, and prepared for physicochemical property analysis in the laboratory.

Plant biomass was determined by the oven-drying method after removing soil particles at 65 °C until constant weight. Soil water content (SWC) was measured using the oven-drying method. Soil pH was determined with a pH meter (water : soil ratio = 2.5 : 1). Bulk density (BD) was measured by the cutting ring method. Soil organic carbon (SOC) was analysed using the potassium dichromate external heating method. Total nitrogen (TN) was determined by the semi-micro Kjeldahl method. Total phosphorus (TP) was measured through sulfuric acid-perchloric acid digestion, while available phosphorus (AP) was analysed by the molybdenum-antimony colourimetric method. Total potassium (TK) was determined using NaOH fusion-flame photometry, and available potassium (AK) was extracted with ammonium acetate for flame photometric measurement (Lu 2000). Soil Na, Ca, Mg, Al, Fe, Mn, Cu, Zn, Ni, Pb, and Co con-

Table 1. Main habitat characteristics of meadows with different degradation degrees

Types	Coverage (%)	Height of vegetation (cm)	Dominant plants	Hole (100 m^2)
NM	96.67 ± 4.71	39.56 ± 2.47	*Kobresia tibetica Maximowicz*, *Blysmus sinocompressus*, *Poa palustris*	0
LDM	75.33 ± 3.68	18.85 ± 2.25	*Kobresia tibetica Maximowicz*, *Roegneria purpurascens*, *Blysmus sinocompressus*	18.00 ± 1.63
MDM	45.67 ± 6.65	9.73 ± 1.53	*Potentilla bifurca*, *Ligularia sibirica*, *Leontopodium leontopodioides*	35.33 ± 3.40
HDM	19.50 ± 1.63	2.52 ± 0.55	*Potentilla anserina*, *Stellera chamaejasme*, *Plantago asiatica*	52.33 ± 2.05

NM – native meadow; LDM – lightly degraded meadow; MDM – moderately degraded meadow; HDM – heavily degraded meadow

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centrations were analysed by inductively coupled plasma atomic emission spectroscopy (ICP-AES, PerkinElmer Avio500, China). Soil Mo concentrations were analysed by inductively coupled plasma atomic emission spectroscopy (ICP-MS, PerkinElmer NexION 350x, China) (Liu et al. 2025).

Calculations and statistical analysis. Statistical analysis was done with SPSS 20.0 (Chicago, USA). A one-way ANOVA following Fisher's *LSD* test was applied to compare differences among treatment means at $P < 0.05$. Pearson's method and redundancy analysis (RDA) were used to analyse the correlation between the data.

RESULTS

Variation of vegetation and soil physicochemical properties in degraded alpine meadows. As shown in Figure 2, alpine meadow degradation progressively reduced vegetation biomass ($P < 0.05$). Aboveground biomass in LDM, MDM, and HDM decreased by 31.33%, 73.38%, and 90.98% versus NM ($P < 0.05$). Underground biomass followed similar trends, with NM highest (1 940.95 g/m²) before sharp degradation-induced declines.

Degradation of alpine meadows significantly reduced SWC, SOC, TN, TP, AN, and AP, while increasing soil BD, pH, TK, and AK ($P < 0.05$) (Table 2). The most pronounced changes were observed in HDM. The results demonstrate degradation's strong impact on soil physicochemical properties, with moisture and nutrients declining as compaction and alkalinity increase.

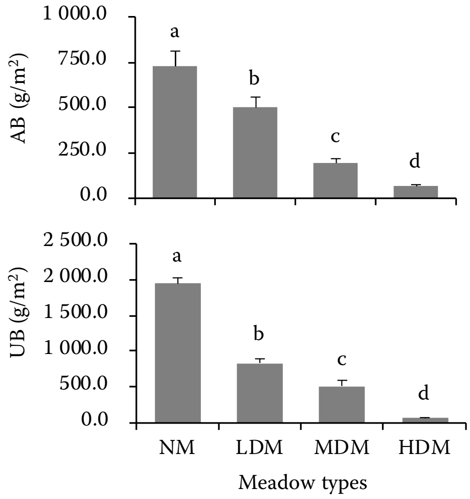

Figure 2. Plant biomass of alpine meadows at different degrees of degradation

AB – aboveground biomass; UB – underground biomass; NM – native meadow; LDM – lightly degraded meadow; MDM – moderately degraded meadow; HDM – heavily degraded meadow; different lowercase letters indicate significant differences among the restoration years at $P < 0.05$

Characteristics of medium and trace element variations in degraded alpine meadow soils. The variation of medium elements in alpine meadow soils is presented in Figure 3, demonstrating a progressive decline in Ca content with increasing degradation severity. Compared to NM, the Ca content decreased by 5.81%, 13.66%, and 15.20% in LDM, MDM, and HDM, respectively. Among them, there were signifi-

Table 2. Soil physicochemical properties in the different reclamation years

Index	NM	LDM	MDM	HDM
SWC (%)	117.72 ± 13.63^{a}	59.15 ± 10.06^{b}	43.14 ± 2.95^{b}	34.14 ± 1.43^{c}
pH	7.24 ± 0.09^{c}	7.48 ± 0.13^{b}	7.57 ± 0.14^{b}	7.80 ± 0.08^{a}
BD (g/cm³)	0.47 ± 0.07^{d}	0.83 ± 0.04^{c}	0.99 ± 0.02^{b}	1.16 ± 0.02^{a}
SOC (g/kg)	185.45 ± 9.32^{a}	120.75 ± 14.92^{b}	86.59 ± 8.65^{c}	49.33 ± 3.41^{d}
TN (g/kg)	11.33 ± 1.15^{a}	7.46 ± 1.08^{b}	5.13 ± 0.28^{c}	3.98 ± 0.60^{d}
TP (g/kg)	1.13 ± 0.20^{a}	0.76 ± 0.08^{b}	0.76 ± 0.05^{b}	0.67 ± 0.04^{b}
TK (g/kg)	10.23 ± 0.85^{b}	16.40 ± 1.98^{a}	17.43 ± 1.17^{a}	18.29 ± 1.08^{a}
AN (mg/kg)	785.36 ± 73.92^{a}	445.56 ± 21.98^{b}	362.94 ± 26.80^{c}	233.98 ± 28.45^{d}
AP (mg/kg)	36.48 ± 2.42^{a}	23.57 ± 4.16^{b}	14.97 ± 2.26^{c}	10.65 ± 2.13^{c}
AK (mg/kg)	117.75 ± 14.66^{d}	170.36 ± 9.89^{c}	308.20 ± 25.41^{b}	402.82 ± 26.44^{a}

NM – native meadow; LDM – lightly degraded meadow; MDM – moderately degraded meadow; HDM – heavily degraded meadow; SWC – soil water content; BD – soil bulk density; SOC – soil organic carbon; TN – total nitrogen; TP – total phosphorus; TK – total potassium; AN – alkaline nitrogen; AP – alkaline phosphorus; AK – alkaline potassium; different lowercase letters indicate significant differences among the restoration years at $P < 0.05$

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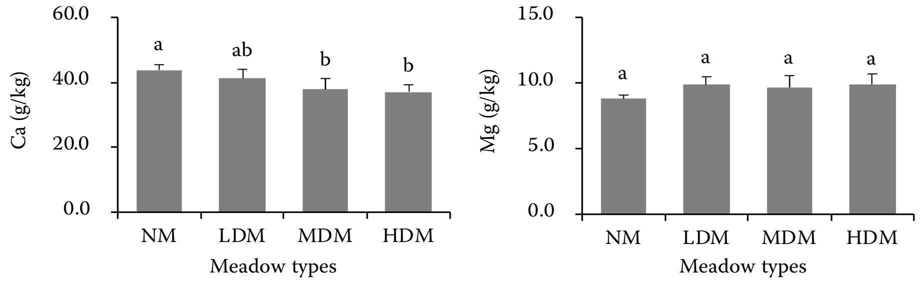

Figure 3. Variation characteristics of medium elements contents in alpine meadow soils under different degradation levels
NM – native meadow; LDM – lightly degraded meadow; MDM – moderately degraded meadow; HDM – heavily degraded meadow; different lowercase letters indicate significant differences among the restoration years at $P < 0.05$

cant differences between NM and both MDM and HDM ($P < 0.05$). After meadow degradation, Mg content increased slightly, but the difference was not significant ($P > 0.05$).

Figure 4 demonstrates the variations in soil trace elements, revealing increasing trends in Fe, Mn, Cu, Ni, and Co contents with progressive degradation severity. with HDM having significantly higher Fe,

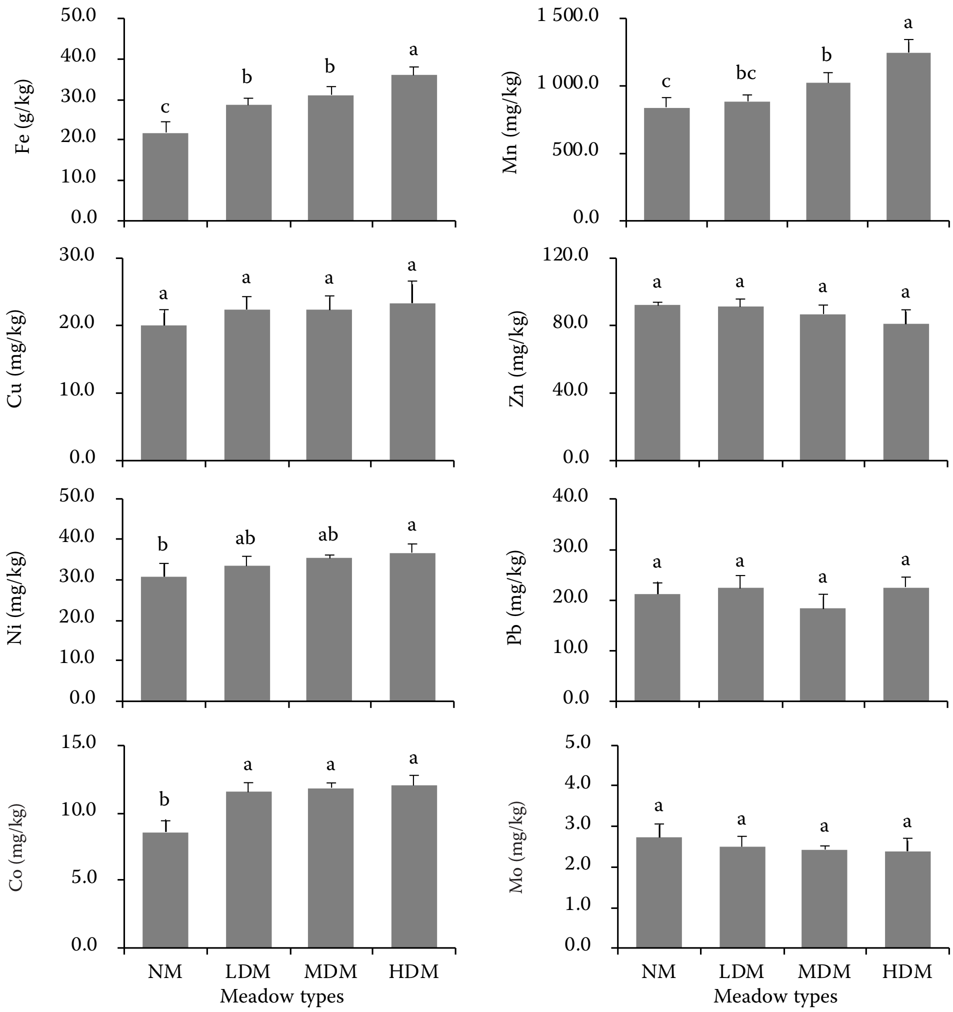

Figure 4. Characteristics of trace elements content variations in alpine meadow soils under different degradation levels
NM – native meadow; LDM – lightly degraded meadow; MDM – moderately degraded meadow; HDM – heavily degraded meadow; different lowercase letters indicate significant differences among the restoration years at $P < 0.05$

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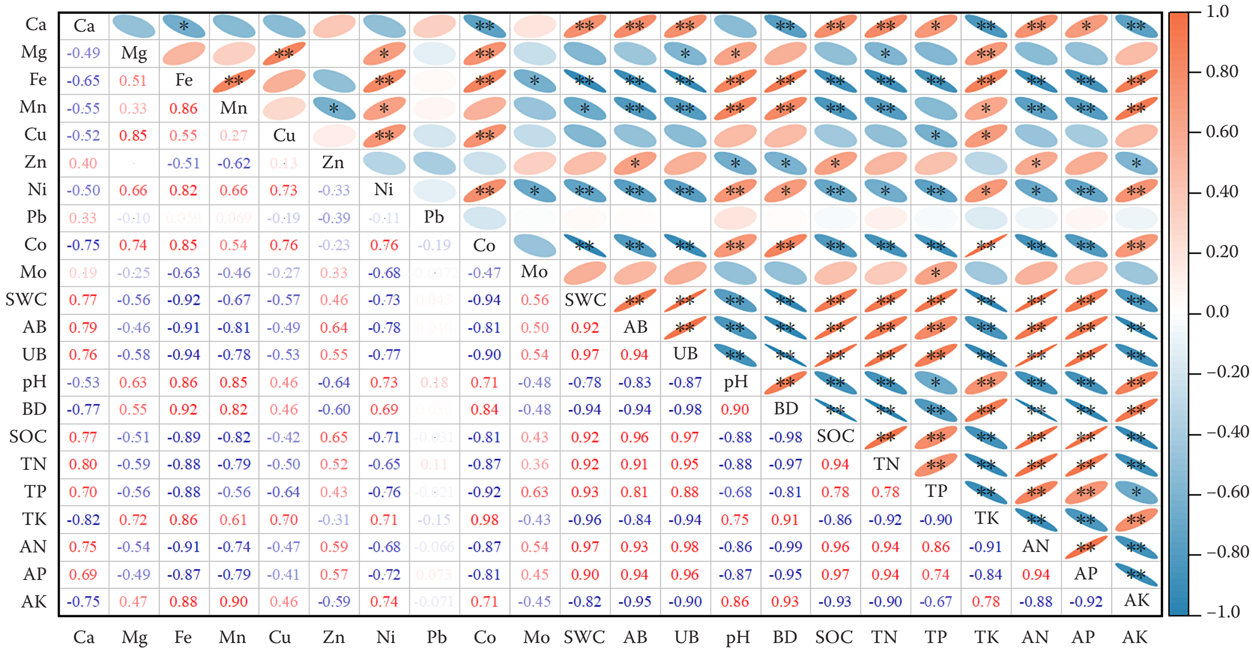

Figure 5. Correlation analysis of plant biomass and soil physicochemical properties with medium and trace elements in alpine meadows

SWC – soil water content; AB – aboveground biomass; UB – underground biomass; BD – soil bulk density; SOC – soil organic carbon; TN – total nitrogen; TP – total phosphorus; TK – total potassium; AN – alkaline nitrogen; AP – alkaline phosphorus; AK – alkaline potassium; *, ** significant at 0.05 and 0.01

Mn, Ni and Co than NM ($P < 0.05$). After meadow degradation, the contents of Zn and Mo decreased slightly, but the differences were not significant ($P > 0.05$). With the intensification of meadow degradation, Pb showed an initial increase, followed by a decrease and then another increase, although the differences were not significant ($P > 0.05$).

Relationships between plant biomass and soil physicochemical properties with medium and trace elements in alpine meadows. Correlation analysis (Figure 5) revealed that soil Ca showed significant positive correlations with SWC, biomass (AB/UB), and nutrients (SOC/TN/TP/AN/AP), while negatively with BD/TK/AK. Mg associated positively with pH/TK but negatively with UB/TN. Fe, Mn, Ni and Co showed positive links with pH/BD/TK/AK but negative correlations with moisture, biomass and nutrients. Cu positively correlated with TP but negatively with TK. Zn exhibited positive associations with AB/SOC/AN but negative with pH/BD/AK. Mo only showed positive correlation with TP ($P < 0.05$).

RDA revealed that the first two axes explained 99.79% and 0.10% of the total variance, respectively (Figure 6). The RDA showed positive correlations between AB, SWC, SOC, TN, TP, AN, AP and the contents of Ca, Mo, and Zn. Conversely, pH, BD, AK, and TK exhibited positive correlations with Mn, Fe, Ni, Co, Mg, and Cu contents.

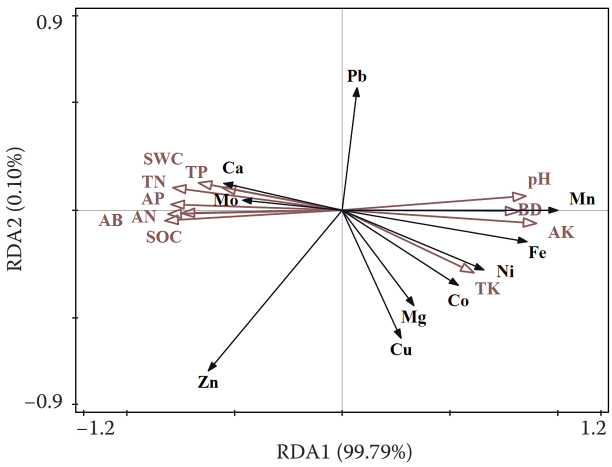

Figure 6. RDA of plant biomass, soil physicochemical properties and medium/trace elements in alpine meadows

SWC – soil water content; AB – aboveground biomass; UB – underground biomass; BD – soil bulk density; SOC – soil organic carbon; TN – total nitrogen; TP – total phosphorus; TK – total potassium; AN – alkaline nitrogen; AP – alkaline phosphorus; AK – alkaline potassium; RDA – redundancy analysis

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DISCUSSION

Vegetation coverage and biomass are key indicators of grassland degradation (Zhang et al. 2024). In alpine meadows, overgrazing and rodent activities significantly reduce vegetation coverage and biomass ($P < 0.05$). These findings align with numerous studies documenting degradation-induced reductions in vegetation parameters (Guo et al. 2019; Zhang et al. 2024). This phenomenon stems from two primary mechanisms: (1) severe degradation correlates with intensive grazing that selectively removes palatable species, leaving low-biomass weeds (e.g., *Stellera chamaejasme* L.) with higher rhizosphere microbial activity that enhances soil nutrient conversion, conferring competitive advantages that exacerbate degradation (Guo et al. 2019); (2) degradation reduces vegetation height and increases bare ground area, creating optimal habitats for rodents that subsequently reduce plant community diversity and stability through selective herbivory, further promoting weed invasion and degradation (Qu et al. 2025).

As the primary site for biological activities in grassland ecosystems, soil properties are inevitably affected by vegetation degradation (Du et al. 2025). This study demonstrates that with increasing degradation intensity in alpine meadows, soil pH and BD show an upward trend, consistent with findings from Yuan et al. (2019) in the Three-River Source Region of the Qinghai-Tibet Plateau. This phenomenon occurs because intensified degradation increases livestock trampling frequency, reduces vegetation coverage and biomass, elevates soil bulk density, and expands bare soil areas, leading to enhanced surface evaporation and decreased soil moisture content. Consequently, soil salts migrate upward with evaporating water, resulting in elevated pH (Yuan et al. 2019). Additionally, reduced vegetation not only decreases plant-derived organic acid secretion but also makes soil organic acids more susceptible to solar radiation damage on exposed surfaces, further contributing to pH increase as organic acid levels decline (Yang et al. 2020). Soil organic matter, nitrogen, phosphorus, and potassium represent key fertility indicators. In this study, progressive meadow degradation significantly reduced SOC, TN, TP, AN, and AP contents, aligning with findings from other degraded alpine grasslands (Dong et al. 2021; Sun et al. 2024). This pattern stems from two mechanisms: (1) without artificial fertilization, grassland ecosystems primarily rely on plant litter for carbon, nitrogen, and phosphorus inputs (Kou et al. 2024), and degradation-induced reductions in vegetation coverage and biomass (Tables 1 and 2) substantially diminish these inputs; (2) increased bare soil area in degraded meadows enhances vulnerability to rainfall erosion and weathering, accelerating organic matter decomposition and facilitating nutrient loss through leaching and surface runoff (Table 2), thereby exacerbating carbon, nitrogen, and phosphorus depletion. Conversely, TK and AK contents increased with degradation severity, consistent with Wang et al. (2019) observations in the Three-River Source Region. This potassium accumulation likely results from accelerated weathering of primary minerals in degraded soils, increasing TK, while reduced vegetation uptake efficiency in degraded meadows contributes to AK accumulation.

Soil medium and trace elements play pivotal physiological and biochemical roles in various metabolic processes within organisms (Xu et al. 2025). The results demonstrate a progressive decline in soil Ca content with increasing degradation intensity in alpine meadows, consistent with findings from Qi et al. (2024) in degraded alpine grasslands of the Qilian Mountains. This reduction primarily stems from: (1) decreased high-quality forage (Table 1), weakening the root-mediated Ca absorption-return cycle; (2) over 50% reduction in root biomass, substantially diminishing biological Ca retention (Hu et al. 2022). Correlation and redundancy analyses (Figures 5 and 6) revealed significant positive associations between SOC and Ca content, where degradation-induced SOC loss reduced colloidal surfaces and Ca^{2+} adsorption sites, ultimately decreasing soil Ca pools (Lan et al. 2025). For Mg, we observed a non-significant increasing trend post-degradation, aligning with Qi et al. (2024)'s results. This pattern reflects two counteracting processes: (1) enhanced weathering of Mg-silicate minerals (e.g., olivine, pyroxene) from exposed parent materials due to reduced vegetation cover; (2) limited Mg release from slow chemical weathering rates characteristic of alpine environments, coupled with reduced plant uptake efficiency (Hu et al. 2022). The net balance of these factors resulted in marginally higher but statistically insignificant soil Mg concentrations across degradation gradients.

The study found that alpine meadow degradation increased the contents of trace elements such as Fe, Mn, Cu, Ni, and Co in the soil. This is because the decrease in SOC weakened its chelation effect on trace

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elements (especially Fe^{3+} and Cu^{2+}), releasing metal ions originally fixed by organic matter into the soil solution (Han et al. 2017). Additionally, degradation led to increased soil bulk density, potentially enhancing anaerobic conditions and promoting reductive dissolution of Fe and Mn (Aumtong et al. 2023). Coupled with relatively higher precipitation in this region compared to other arid grasslands (annual precipitation 600–700 mm) (Luo et al. 2022), these trace elements were leached, as confirmed by correlation analysis and RDA results (Figure 5 and 6). The study found that after meadow degradation, soil Zn and Mo contents decreased but not significantly. Zn and Mo readily form complexes with organic matter, and meadow degradation caused significant SOC decline, directly weakening the adsorption capacity for Zn and Mo (Louis et al. 2014; Shi et al. 2023). Under sufficient precipitation conditions, they were prone to leaching loss. However, the reduction of high-quality forage (correlation analysis and RDA results showed negative correlations between plant biomass and Zn/Mo) also decreased the uptake of soil Zn and Mo, resulting in insignificant reductions of soil Zn and Mo. Pb showed a trend of initial increase, followed by a decrease, and then an increase with intensifying degradation. This may be because in early degradation stages, decomposition of litter and roots released some organically-bound Pb, causing a short-term increase (Song et al. 2015). When vegetation was substantially reduced, enhanced soil anaerobic conditions and increased Fe/Mn contents strengthened Pb adsorption capacity, leading to a slight increase in soil Pb content under severe degradation (Zheng et al. 2022).

CONCLUSION

In conclusion, alpine meadow degradation significantly reduced surface coverage, height, and vegetation biomass, with belowground biomass showing the highest decrease (56.88–95.18%). It decreased SWC, SOC, nitrogen, and phosphorus contents, while increasing soil BD, pH, and potassium contents. Among soil medium and trace elements, meadow degradation significantly reduced soil Ca, Zn and Mo content but increased soil Mg, Fe, Mn, Cu, Ni, and Co content. Correlation analysis and RDA results showed positive correlations between AB, SWC, SOC, TN, TP, AN, AP and Ca, Mo, Zn contents, while pH, BD, AK, TK were positively correlated with Mn, Fe, Ni, Co, Mg, and Cu. In summary, alpine meadow degradation reduced vegetation coverage and biomass, deteriorated soil properties, and altered medium and trace element contents. Future degraded grassland management and restoration should consider regulating elements like Ca, Fe, and Mn in addition to macronutrients and basic soil properties. These findings provide fundamental data for the ecological restoration of degraded alpine meadows.

REFERENCES

Aumtong S., Chotamonsak C., Pongwongkam P., Cantiya K. (2023): Chemical fertilization alters soil carbon in paddy soil through the interaction of labile organic carbon and phosphorus fraction. Agronomy, 13: 1588.

Chen X., He L., Luo F., He Z.W., Bai W.Q., Xiao Y.X., Wang Z.F. (2023): Dynamic characteristics and impacts of ecosystem service values under land use change: A case study on the Zoigê plateau, China. Ecological Informatics, 78: 102350.

Dong L., Li J.J., Sun J., Yang C. (2021): Soil degradation influences soil bacterial and fungal community diversity in overgrazed alpine meadows of the Qinghai-Tibet Plateau. Scientific Reports, 11: 11538.

Du Z.Y., Cong N., Zhao G., Zheng Z.T., Wang D.L., Wang X.T., Cai M.K., Guo Y.Y., Zhang Y.J. (2025): Divergent responses of vegetation and soil characteristics to grassland degradation in the Qinghai-Tibet and Inner Mongolia plateaus. Catena, 257: 109146.

Guo N., Degen A.A., Deng B., Shi F.Y., Bai Y.F., Zhang T., Long R.J., Shang Z.H. (2019): Changes in vegetation parameters and soil nutrients along degradation and recovery successions on alpine grasslands of the Tibetan plateau. Agriculture, Ecosystems & Environment, 284: 106593.

Han Z.X., Wan D.J., Hu J.P., Liu L., Liu Q., Ni T.Y. (2017): Migration and transformation of heavy metals in soil and its influencing factors. Multipurpose Utilization of Mineral Resources, 6: 5–9.

Heine G., Max J.F.J., Führs H., Moran-Puente D.W., Heintz D., Horst W.J. (2011): Effect of manganese on the resistance of tomato to *Pseudocercospora fuligena*. Journal of Plant Nutrition and Soil Science, 174: 827–836.

Hu J., Zhou D.W. (2024): Distributions of trace elements with long-term grazing exclusion in a semi-arid grassland of Inner Mongolia. Ecology and Evolution, 14: e70072.

Hu J., Li Q., Huang Y.X., Zhang Q.L., Zhou D.W. (2022): Distributions of medium mineral elements with long-term grazing exclusion in a semi-arid grassland of Inner Mongolia. Ecological Indicators, 143: 109384.

Kou X.X., Mou X.M., Xu W.B., Xi S.G., Yu Y.W. (2024): Yak and Tibetan sheep dung increase the proportional biomass of grasses and alleviate soil nitrogen limitation in degraded Tibetan alpine grassland. Catena, 240: 108007.

Lan J.C., Jiang Y.X., Huang M.Z. (2025): Vegetation restoration enhances soil organic carbon accumulation in Southwest China's karst region: The role of aggregation, calcium, and microbes. Catena, 257: 109184.

https://doi.org/10.17221/91/2025-SWR

Li H.Y., Qiu Y.Z., Ma L., Yao X.N. (2024): Soil ecological stoichiometry reveals microbial nutrient limitation with alpine meadow degradation in Northeastern Tibetan Plateau. Catena, 246: 108358.

Liu Z.H., Jia C.Y., Fan F.C., Dai S.J., Li X.J. (2025): Speciation analysis and related models of heavy metals in contaminated soil. Multipurpose Utilization of Mineral Resources, 46: 97–106.

Louis Y., Pernet-Coudrier B., Varrault G. (2014): Implications of effluent organic matter and its hydrophilic fraction on zinc(II) complexation in rivers under strong urban pressure: Aromaticity as an inaccurate indicator of DOM–metal binding. Science of The Total Environment, 490: 830–837.

Lu R.K. (2000): Chemical Analysis Method of Agricultural Soil. Beijing, China Agricultural Technology Press. (in Chinese)

Luo H.Q., Yu J.L., Li R.X., Gu J.D., Luo L., Zhang Y.Y., He Y., Xiao Y.L., Deng S.H., Zhang Y.Z., Zhang S.R., Wang L.L., He J.S., Deng O.P., Lan T. (2022): Microbial biomass C : N : P as a better indicator than soil and ecoenzymatic C : N : P for microbial nutrient limitation and C dynamics in Zoige Plateau peatland soils. International Biodeterioration & Biodegradation, 175: 105492.

Mu Z.B., Asensio D., Sardans J., Ogaya R., Llusià J., Filella I., Liu L., Wang X.M., Peñuelas J. (2023): Chronic drought alters extractable concentrations of mineral elements in Mediterranean forest soils. Science of The Total Environment, 905: 167062.

Qi H., Tong J., He G.X., Xu H.G., Li Y.L., Yang Z.L., Wang Y.J., Ma C.L., Li Q., Liu X.N. (2024): Response of soil physical properties to trace element content and degradation degree in mountain meadow of eastern Qilian Mountains. Acta Agrestia Sinica, 32: 746–753.

Qian H.Y., Chen Z.Y., Feng X.X., Zhou N.D., Luo Y.J., Pu Y.L., Hu Y.H. (2024): Content and spectral characteristics of soil dissolved organic matter in alpine meadows with different degree. Acta Agrestia Sinica, 32: 3715–3721.

Qu G.P., Zhao J.X., Wu G.L. (2025): Elevational amplification of plateau pika (Ochotona curzoniae) burrowing impacts on ecological functions in alpine grasslands. Journal of Environmental Management, 387: 125868.

Rai S., Singh P., Mankotia S., Swain J., Satbhai S.B. (2021): Iron homeostasis in plants and its crosstalk with copper, zinc, and manganese. Plant Stress, 1: 100008.

Shi T.Y., Liu Z.H. Hu Q.M., Yang S.T., Liu J., Jing L.D. (2025): Periphyton as a nature-based solution for remediation of degraded Zoige alpine wetlands: Process, effects and evaluation. Journal of Environmental Management, 377: 124647.

Shi Y.X.X., Yu Y.J., Xiang M.D., Cui P.X., Cui J.Q., Zhang F., Jiang J., Xu R.K. (2023): Changes in molybdenum bioaccessibility in four spiked soils with respect to soil pH and organic matter. Journal of Environmental Management, 334: 117476.

Song X.L., Wang Y.J., Zhang Z., Wang M., Wang S., Guo G.L. (2015): Impact of Organic Matter Removal on Phosphate-Induced Pb Stabilization in Soil. Journal of Agro-Environment Science, 34: 1522–1527.

Sun H.R., Liu J.Y., Wu J.H., Hu H.Y., Chen Q.B., Fang H.Y., Tao K. (2024): Effects of alpine grassland degradation on soil microbial community structure and metabolic activity in the Qinghai-Tibet Plateau. Applied Soil Ecology, 200: 105458.

Wang Y.Q., Yin Y.L., Li S.X. (2019): Physicochemical properties and enzymatic activities of alpine meadow at different degradation degrees. Ecology and Environmental Sciences, 28: 1108–1116.

Xu X.N., Yang Q.W., Xiang G.P., Liu T., Yang M.J., Xiong X., Jiang T. (2023): Comprehensive evaluation of the Ruoergai Prairie ecosystem upstream of the Yellow River. Frontiers in Ecology and Evolution,10: 1047896.

Xu Z.Q., Zhou Y.Z., Liu R., Cui H.J., Tan J., Zhou W.J., Ouyang K. (2025): Available medium and micronutrients in the soils of major citrus-producing areas in Southeast China. Journal of Environmental Management, 389: 126078.

Yang J., Liu Q.R., Wang X.T. (2020):Plant community and soil nutrient of alpine meadow in different degradation stages on the Tibetan Plateau, China. Chinese Journal of Applied Ecology, 31: 4067–4072.

Yuan Z.Q., Jiang X.J., Liu G.J., Jin H.J., Chen J., Wu Q.B. (2019): Responses of soil organic carbon and nutrient stocks to human-induced grassland degradation in a Tibetan alpine meadow. Catena, 178: 40–48.

Zhang G.Y., Zhao C.P., Jia M.M., Zhang R., Jiang H., Wang Z.M. (2025a): Mapping dominant plant communities in the degraded Zoige swamp using Sentinel-1/2 imagery and its implications for vegetation restoration. Ecological Indicators, 175: 113557.

Zhang K.C., Pan J.P., An Z.S., Zhang Y., Yu Y.P. (2024): Effects of alpine meadow degradation on the soil physical and chemical properties in Maqu, China. Research in Cold and Arid Regions, 16: 269–277.

Zhang K.X., Ning L.B., Ning K.Z., Jin Z.H., Wang X.P., Zhu H.S. (2025b) Structural characteristics and spatial heterogeneity of vegetation and below-ground habitat during the long-term succession of ecosystems in mining areas. Ecological Engineering, 215: 107601.

Zheng Y.H., Li Y.T., Zhang Z.G., Tan Y.N., Cai W.Q., Ma C.N., Chen F.L., Lu J.W. (2022): Effect of low-molecular weight organic acids on migration characteristics of Pb in reclaimed soil. Frontiers in Chemistry, 10: 934949.

Zhu Q., Zhang M., Ma Q. (2012): Copper-based foliar fertilizer and controlled release urea improved soil chemical properties, plant growth and yield of tomato. Scientia Horticulturae, 143: 109–114.

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