Responses of Soil Physicochemical Properties to Elevation and Slope Aspect and Their Relationships with Vegetation Characteristics in Alpine Meadows of the Eastern Qilian Mountains: Postprint

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Abstract

To explore the response of soil physicochemical properties to elevation and slope aspect and their relationship with vegetation in alpine meadows, this study took alpine meadows in the Eastern Qilian Mountains as the research object, and analyzed the variation patterns of soil nutrient contents and ecological stoichiometric ratios across 7 elevation gradients and 2 slope aspects, as well as their relationships with vegetation. The results showed that: (1) Soil water content, electrical conductivity, organic carbon, total nitrogen, total potassium, alkali-hydrolyzable nitrogen, available phosphorus, available potassium contents, carbon/phosphorus ratio (C/P) and nitrogen/phosphorus ratio (N/P) exhibited a trend of first increasing and then decreasing with increasing elevation, while soil bulk density, total phosphorus and carbon/nitrogen ratio (C/N) showed a trend of first decreasing and then increasing. (2) At the same elevation, soil soil bulk density, available potassium, electrical conductivity and total phosphorus on sunny slopes were higher than those on shady slopes at most elevation gradients, while soil water content, available phosphorus, C/P and N/P on sunny slopes were lower than those on shady slopes; below the 3200 m elevation gradient, soil organic carbon, total nitrogen, alkali-hydrolyzable nitrogen and C/N on sunny slopes were lower than those on shady slopes. (3) The C/N, C/P and N/P ratios of alpine meadow soils at different elevations and slope aspects ranged between 14.55–38.13, 12.61–87.94 and 0.27–5.01, respectively. (4) Redundancy Analysis (RDA) revealed that soil bulk density, total nitrogen and available phosphorus were the key soil factors affecting alpine meadow vegetation, and cluster analysis found that shady and sunny slopes at 3200–3400 m elevation clustered into one group. In summary, soil nutrients and ecological stoichiometric ratios in alpine meadows of the Eastern Qilian Mountains exhibited regular

changes with elevation and slope aspect. Based on the analysis of N/P ratio, the primary productivity of alpine meadow grasslands in this region was mainly limited by soil nitrogen, particularly evident in low and high elevation areas. Based on cluster analysis, elevations of 3000 m and 3400 m were identified as critical thresholds where vegetation and soil characteristics changed in this region. It is recommended that the differential characteristics of elevation and slope aspect should be fully considered in the management of alpine meadow grasslands.

Full Text

Response of Soil Physical and Chemical Properties to Altitude and Aspect in Alpine Meadows of the Eastern Qilian Mountains and Their Relationships with Vegetation Characteristics

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Abstract

To explore the response of soil physicochemical properties to altitude and aspect and their relationships with vegetation in alpine meadows, we investigated soil nutrient content and ecological stoichiometric ratios across different elevations and slopes in the eastern Qilian Mountains. The results revealed: (1) Soil water content, electrical conductivity, organic carbon, total nitrogen, total potassium, alkali-hydrolyzable nitrogen, available phosphorus, and available potassium, as well as the carbon-phosphorus ratio (C/P) and nitrogen-phosphorus ratio (N/P), exhibited a trend of initial increase followed by decrease with rising altitude. In contrast, soil bulk density, total phosphorus, and the carbon-nitrogen ratio (C/N) showed the opposite pattern of initial decrease followed by increase. (2) At the same altitude, most elevations showed higher soil bulk density, available potassium, electrical conductivity, and total phosphorus on sunny slopes compared to shady slopes, while soil water content, available phosphorus, C/P, and N/P were lower on sunny slopes. Below 3200 m, soil organic carbon, total nitrogen, alkali-hydrolyzable nitrogen, and C/N on sunny slopes were lower than on shady slopes. (3) The C/N, C/P, and N/P ratios of alpine meadow soils across different altitudes and aspects ranged between 14.55–38.13, 12.61–87.94, and 0.27–5.01, respectively. (4) Redundancy analysis (RDA) identified soil bulk density, total nitrogen, and available phosphorus as the key soil factors influencing alpine meadow vegetation. Cluster analysis grouped shady and sunny slopes at 3200–3400 m altitude into one category. In conclusion, soil nutrients and stoichiometric ratios in the eastern Qilian Mountains' alpine meadows vary systematically with altitude and aspect. Analysis of N/P ratios indicates that primary productivity in this region's alpine meadow steppe is primarily limited by soil nitrogen, particularly pronounced in low- and high-altitude zones. Cluster analysis reveals that 3000–3400 m represents a critical threshold where vegetation and soil characteristics shift. We recommend that management of alpine meadow steppe should fully consider the differential effects of altitude and aspect.

Keywords: alpine meadow; altitude; aspect; ecological stoichiometry; redundancy analysis (RDA)

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1 Introduction

Soil serves as the fundamental substrate for plant growth in grassland ecosystems, directly influencing vegetation community structure and productivity. Soil nutrients constitute the primary source of plant nutrients, where variations in content, elemental balance, and physical structure are key factors regulating plant growth and distribution. Soil ecological stoichiometry characterizes nutrient limitation in organisms and populations, as well as ecosystem structure and function, with metrics such as carbon-nitrogen ratio (C/N) and carbon-phosphorus ratio (C/P) reflecting soil nitrogen and phosphorus supply capacity and decomposition rates, while nitrogen-phosphorus ratio (N/P) indicates nutrient limitation in soil nitrogen and phosphorus supply. He et al. (2010) articulated the unified theory of ecological stoichiometry from individual to ecosystem levels and its nutrient limitation framework, while Chen et al. (2021) and Sun et al. (2021) synthesized research findings on ecological stoichiometry in China's typical ecologically vulnerable regions and natural grasslands. Topographic factors influence soil nutrient distribution and accumulation by affecting material and energy exchange between soil and environment, interacting with other soil-forming factors to shape soil ecological stoichiometric characteristics. Altitude and aspect are primary topographic factors in mountain ecosystems that affect regional hydrothermal conditions, thereby influencing soil nutrient distribution patterns and stoichiometric ratios. Investigating grassland soil physicochemical properties and ecological stoichiometric characteristics reveals plant-soil nutrient relationships, enhances understanding of nutrient cycling and balance mechanisms, and is crucial for assessing soil quality and managing grasslands rationally. Understanding how soil nutrient content and stoichiometric characteristics change with topographic factors holds significant ecological importance.

The study area is located in the upper Jinqiang River basin of the eastern Qilian Mountains in Zhua Xiu Long Township, Tianzhu Tibetan Autonomous

County, Gansu Province (37°17 53 N, 102°26 31 –102°55 01 E), at 2800–4000 m elevation. The Qilian Mountains represent a critical ecological security barrier in northwest China, with alpine meadow being the primary grassland type that plays a pivotal role in regional ecosystem stability. The region features a cold-humid climate with mean annual temperatures of -0.1–0.6°C, annual precipitation of 446 mm, annual evaporation of 1360–1614 mm, and mean relative humidity of 70–75%. The main grassland type is alpine meadow, with soil types including subalpine meadow soil, mountain chernozem, and mountain meadow soil. Previous studies in the Qilian region found that soil nutrients generally decrease with altitude, peaking at mid-high elevations, with vegetation type, altitude, aspect, and coverage being primary influencing factors. However, research specifically examining soil physicochemical properties and ecological stoichiometric characteristics of alpine meadow systems in response to altitude and aspect interactions remains unreported. Understanding these interactive effects is essential for revealing nutrient deficiency and limitation patterns in regional alpine meadows and informing rational grassland management.

This study investigates soil physicochemical properties and ecological stoichiometric variations across different altitudes and aspects in eastern Qilian alpine meadows and their relationships with vegetation characteristics, aiming to provide scientific data for rational management and ecological conservation of alpine meadows.

1.1 Study Area Overview

The study area spans coordinates 37°07 23 –37°17 54 N, 102°25 52 –102°55 01 E, covering elevations from 2800 m to 4000 m. The region's cold-humid climate supports alpine meadow vegetation on subalpine meadow soils, mountain chernozems, and mountain meadow soils.

1.2 Sample Plot Setup and Sample Collection

During July 6–17, 2019, we established sample plots at seven altitudes (2800 m, 3000 m, 3200 m, 3400 m, 3600 m, 3800 m, 4000 m) with two aspects (sunny and shady) at each elevation in the Jinqiang River basin of the eastern Qilian Mountains. All sampling areas were within grazing-excluded zones. At each plot, three 10 m × 10 m quadrats were randomly selected, with three 50 cm × 50 cm sub-quadrats established along diagonals. Vegetation height and total coverage were measured using calipers and point-intercept methods, with species-specific height and coverage recorded. Aboveground biomass was harvested at ground level, fresh-weighed, oven-dried at 105°C for 30 minutes, then at 65°C to constant weight. After harvesting, soil cores (0–30 cm depth) were collected using a 5 cm diameter soil auger for nutrient analysis, while soil bulk density and water content were measured using ring samples.

1.3 Soil Physicochemical Property Measurements

Soil bulk density and water content were determined using the ring method and oven-drying method, respectively. Soil water-holding capacity was measured following methods from the Laboratory of Physics, Nanjing Institute of Soil Science, Chinese Academy of Sciences (1987). For pH and electrical conductivity, air-dried soil was sieved (2 mm), mixed with deionized water at a 1:2.5 soil-water ratio, shaken at 150 rpm for 10 minutes, and measured using a pH meter and conductivity meter.

For total nutrients, air-dried soil was sieved (0.25 mm) and ground to <0.15 mm. Soil organic carbon (SOC) was measured using a Multi N/C 2100S/1 automatic carbon analyzer (Analytik Jena AG, Germany). Total nitrogen (TN) was determined by the Kjeldahl method, total phosphorus (TP) by molybdenum-antimony colorimetry, and total potassium (TK) by sodium hydroxide fusion-flame photometry. For available nutrients, air-dried soil was sieved (2 mm) and ground to <0.25 mm. Available nitrogen (AN) was measured by diffusion absorption, available phosphorus (AP) by molybdenum-antimony colorimetry (with permanganate oxidation-glucose reduction decolorization for high organic matter soils, following Zhang et al. 1995), and available potassium (AK) by ammonium acetate-flame photometry.

1.4 Data Processing and Analysis

Data were processed using Excel 2010 and SPSS 21.0 for ANOVA and significance testing. Canoco 5.0 was used for redundancy analysis (RDA) and cluster analysis to examine heterogeneity in soil physicochemical properties and ecological stoichiometry across altitudes and aspects and their relationships with vegetation.

2 Results

2.1 Vegetation Characteristics Across Altitudes and Aspects

Vegetation coverage initially increased then decreased with altitude, peaking at 3200 m for both aspects (80.00% for sunny slopes, 96.67% for shady slopes). Shady slopes consistently showed higher coverage than sunny slopes, with significant differences at all altitudes except 4000 m. Grass height and aboveground biomass followed similar patterns, peaking at 3200 m .

2.2 Soil Bulk Density, Water Content, pH, and Electrical Conductivity

The interaction of altitude and aspect significantly affected soil bulk density, water content, pH, and electrical conductivity ($P < 0.05$). Soil bulk density decreased initially then increased with altitude, reaching minima at 3200 m ($0.68\ g \cdot cm^{-3}$ for sunny slopes, $0.66\ g \cdot cm^{-3}$ for shady slopes). Shady slopes had lower bulk density than sunny slopes at all altitudes. Soil water content increased then decreased, peaking at 3200 m (64.36% for sunny slopes, 52.18% for shady slopes), with shady slopes showing higher values than sunny slopes at all altitudes except 3600 m ($P < 0.05$). Soil pH on sunny slopes increased then decreased then increased again, while on shady slopes it decreased then increased, with maxima and minima at different altitudes. Electrical conductivity increased then decreased with altitude, peaking at 3000 m for sunny slopes (249.00 $S \cdot cm^{-1}$) and 3200 m for shady slopes (195.83 $S \cdot cm^{-1}$), with sunny slopes showing significantly higher values than shady slopes at most altitudes [Figure 1: see original paper].

2.3 Soil Nutrient Content Variations

The altitude-aspect interaction significantly affected SOC, TN, TP, and TK ($P < 0.05$). SOC and TN increased then decreased, peaking at 3200 m (85.66 $g \cdot kg^{-1}$ SOC and 4.45 $g \cdot kg^{-1}$ TN for sunny slopes; 99.26 $g \cdot kg^{-1}$ SOC and 5.01 $g \cdot kg^{-1}$ TN for shady slopes). Shady slopes had higher SOC and TN than sunny slopes at all altitudes except 2800 m and 3000 m, with significant differences at 3200 m ($P < 0.05$). TP decreased then increased, reaching minima at 3800 m (0.54 $g \cdot kg^{-1}$ for sunny slopes, 0.77 $g \cdot kg^{-1}$ for shady slopes), with sunny slopes having higher TP than shady slopes at most altitudes. TK increased then decreased, peaking at 3600 m for sunny slopes (14.45 $g \cdot kg^{-1}$) and 3400 m for shady slopes (12.24 $g \cdot kg^{-1}$), with aspect differences varying by altitude [Figure 2: see original paper].

Soil AN followed similar patterns to SOC, while AP and AK increased then decreased, peaking at 3200 m (AP: 28.75 $mg \cdot kg^{-1}$ for sunny slopes, 24.62 $mg \cdot kg^{-1}$ for shady slopes; AK: 286.61 $mg \cdot kg^{-1}$ for sunny slopes, 221.06 $mg \cdot kg^{-1}$ for shady slopes). Shady slopes had higher AN and AP than sunny slopes at most altitudes, while AK was lower on shady slopes [Figure 3: see original paper].

2.4 Soil Ecological Stoichiometric Ratios

Soil C/N, C/P, and N/P ratios varied significantly with altitude and aspect. C/N decreased then increased, reaching minima at 3200 m for sunny slopes (14.55) and 3000 m for shady slopes (18.01). Sunny slopes had lower C/N than shady slopes at 2800 m and 3400 m, but higher C/N at other altitudes. C/P increased then decreased, peaking at 3800 m (87.94 for sunny slopes, 38.13 for shady slopes), with sunny slopes generally lower than shady slopes except at 4000 m. N/P increased then decreased, with values ranging 0.27–5.01 across all sites, indicating nitrogen limitation [Figure 4: see original paper].

2.5 Relationships Between Soil Factors and Vegetation Characteristics

Redundancy analysis showed that vegetation characteristics were most strongly influenced by soil bulk density, TN, and AP, with bulk density negatively correlated and TN and AP positively correlated with vegetation metrics. The first two RDA axes explained 95.18% of the variation, indicating strong representation of soil-vegetation relationships [Figure 5: see original paper].

Cluster analysis based on vegetation, soil physicochemical properties, and stoichiometric ratios grouped the sites into two categories: low-mid altitude (2800–3400 m) and high altitude (3600–4000 m), with aspect differences more pronounced at lower altitudes. The 3000–3400 m zone emerged as a critical transition line for vegetation and soil characteristics.

3 Discussion

3.1 Soil Physical Properties

Soil bulk density and water content are key indicators of soil physical quality, influencing nutrient cycling, enzyme activity, and chemical reactions. Electrical conductivity reflects soil nutrient status and quality. Our findings show that bulk density decreased then increased with altitude, while water content and conductivity increased then decreased, consistent with studies by Liu et al. (2019) and Feng et al. (2020). Aspect differences arise from differential solar radiation and evaporation, with sunny slopes having higher bulk density, conductivity, and lower water content than shady slopes, similar to results from Lü et al. (2020). At high altitudes (>3400 m), low temperatures limit plant growth and root activity, reducing vegetation cover and soil water content, while at moderate altitudes (3200 m), optimal conditions enhance root activity and reduce bulk density.

3.2 Soil Nutrients

Soil organic carbon directly reflects soil fertility. Our results show SOC, TN, TK, AN, AP, and AK peaked at 3200 m then declined, while TP showed the opposite pattern. This contrasts with some regional studies, likely due to localized differences in phosphorus distribution. Altitude effects on temperature influence plant litter input and microbial activity, with moderate elevations promoting organic matter accumulation and nutrient availability. Aspect effects on water-heat redistribution are more pronounced at lower altitudes, while high-altitude cold conditions diminish these differences. Sunny slopes receive more radiation, increasing evaporation and altering nutrient distribution patterns.

3.3 Soil Ecological Stoichiometry

Soil stoichiometric ratios reflect internal nutrient cycling and indicate ecosystem carbon sequestration capacity. Our C/N ratios (14.55–38.13) and C/P ratios (12.61–87.94) showed altitude-dependent patterns, with sunny slopes generally having lower C/P than shady slopes except at high elevations. N/P ratios (0.27–5.01) indicate nitrogen limitation across all sites, particularly severe at low and high altitudes. According to established thresholds ($N/P < 10$ indicates nitrogen limitation; $N/P > 20$ indicates phosphorus limitation), our results confirm nitrogen as the primary limiting nutrient for alpine meadow productivity. The low N/P ratios on sunny slopes compared to shady slopes suggest stronger nitrogen limitation in more exposed conditions.

3.4 Key Soil Factors Influencing Alpine Meadow Vegetation

Vegetation and soil are interdependent components of alpine grassland ecosystems. Changes in vegetation alter soil properties, which in turn feedback to affect plant traits and litter decomposition, influencing sustainability. Our RDA identified bulk density, TN, and AP as the critical soil factors affecting vegetation, consistent with Li (2019). Cluster analysis revealed 3000–3400 m as the critical transition zone where vegetation and soil characteristics shift significantly. This threshold should guide management strategies, with differential approaches needed for zones below and above this elevation range.

4 Conclusion

Based on our investigation of soil physicochemical properties and vegetation characteristics across altitudes and aspects in eastern Qilian alpine meadows:

1) Soil water content, electrical conductivity, SOC, TN, TK, AN, AP, AK, C/P, and N/P increased then decreased with altitude, while bulk density, TP, and C/N showed the opposite pattern.
2) At the same altitude, sunny slopes generally had higher bulk density, AK, conductivity, and TP but lower water content, AP, C/P, and N/P than shady slopes. Below 3200 m, sunny slopes also had lower SOC, TN, AN, and C/N.
3) Analysis of N/P ratios reveals that alpine meadow primary productivity is primarily limited by soil nitrogen, especially pronounced in low- and high-altitude areas.
4) RDA and cluster analysis identified bulk density, TN, and AP as key soil factors influencing vegetation, with 3000–3400 m representing the critical transition line for vegetation and soil characteristics.

We recommend that management of alpine meadow steppe should incorporate altitude and aspect differentiation into planning and implementation to promote sustainable ecosystem development.

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Note: Figure translations are in progress. See original paper for figures.