Altitudinal Distribution Patterns of Soil Nutrients in Tianshan Spruce Forests Across Different Regions and Their Evaluation: Postprint

Authors: Xu Dong, Chen Hao, Yeerjiang · Baiketuerhan, Wang Qiang

Date: 2025-09-01T11:34:36+00:00

Abstract

To investigate the spatial distribution differences of soil nutrients in the understory of Tianshan spruce forests and provide a foundation for forest health assessment of Tianshan spruce (Picea schrenkiana var. tian schanica) forests, experiments were conducted in four study areas selected across four different longitude ranges from east to west on the northern slopes of the Tianshan Mountains. Sample lines and plots were established along altitude gradients, and soil nutrient distribution patterns and differences across regions and altitudes were analyzed through sampling, with final evaluations performed. The results showed that: (1) Altitude had a certain influence on the distribution of organic matter, total nitrogen, and total phosphorus contents. (2) There existed significant positive correlations among organic matter content, total nitrogen content, and total phosphorus content in soil nutrients. (3) The overall performance of soil nutrient content at different altitudes, from high to low, was as follows: mid-high altitude (96.3 points), high altitude (95.5 points), mid altitude (95.0 points), mid-low altitude (88.5 points), and low altitude (79.4 points); the performance of soil nutrient ratings in different regions, from high to low, was as follows: western Tianshan (93.4 points), mid-eastern Tianshan (91.4 points), mid-western Tianshan (91.0 points), and central Tianshan (88.0 points). (4) The distribution of total potassium content was more stable across all altitudes, being minimally affected by altitude factors. (5) Soil nutrients in Tianshan spruce forests on the northern slopes of the Tianshan Mountains were generally abundant, but still exhibited certain differences across different altitudes and regions, with the highest nutrient content ratings observed in the western Tianshan region and the mid-high altitude zone.

Full Text

Preamble

ARID LAND GEOGRAPHY Vol. 48 No. 8 Aug. 2025

Distribution patterns and evaluation of soil nutrients in *Picea schrenkiana* var. *tianschanica* forests across different regions and altitudes

XU Dong, CHEN Hao, Yeerjiang BAIKETUERHAN, WANG Qiang

(College of Forestry and Landscape Architecture, Xinjiang Agricultural University/Key Laboratory of Forestry Ecology and Industrial Technology in Arid Areas of Xinjiang, Urumqi, Xinjiang)

Abstract

To investigate the spatial variability of soil nutrients under *Picea schrenkiana* var. *tianschanica* forests and provide a scientific basis for forest health evaluation, an experiment was conducted across four study areas located along different longitude ranges from east to west on the northern slope of the Tianshan Mountains. Sample lines and plots were established along elevation gradients, and soil samples were collected to analyze nutrient distribution patterns and differences across regions and elevations. The results indicated the following: (1) Elevation had a certain influence on the distribution of soil organic matter, total nitrogen, and total phosphorus content. (2) Soil organic matter, total nitrogen, and total phosphorus contents were significantly positively correlated. (3) Based on a comprehensive evaluation, the ranking of soil nutrient content across different elevations, from highest to lowest, was as follows: Mid-high elevation (96.3 points), high elevation (95.5 points), mid elevation (95.0 points), mid-low elevation (88.5 points), and low elevation (79.4 points); across different regions, the soil nutrient rankings were: Western Tianshan (93.4 points), mid-eastern Tianshan (91.4 points), mid-western Tianshan (91.0 points), and central Tianshan (88.0 points). (4) Total potassium content exhibited more stable distribution across elevations, with minimal influence from elevation factors. (5) Overall, soil nutrient levels under *Picea schrenkiana* var. *tianschanica* forests on the northern slope of the Tianshan Mountains were generally abundant, although certain differences still existed across elevations and regions. The highest nutrient content was observed in western Tianshan and the mid-high elevation zone.

Keywords: northern slope of the Tianshan Mountains; *Picea schrenkiana* var. *tianschanica* forests; soil nutrients; altitude; nutrient rating

Introduction

The importance of soil in forest ecosystems has long been widely recognized. As a core component of forest ecological processes, soil serves as a critical source of nutrients required for tree growth and provides the foundation for forest development by supporting and anchoring trees. All essential ecological elements for tree growth—including water, nutrients, air, and heat—are provided through soil, playing a pivotal role in the natural succession of forest ecosystems. Soil organic matter content not only influences soil physical, chemical, and ecological characteristics but also determines soil fertility and ecosystem stability. Nitrogen is the element most demanded by plants, and soil total nitrogen content represents an important indicator of soil fertility. Phosphorus in soil participates not only in essential life processes such as photosynthesis and respiration but also directly affects ecosystem nutrient cycling. Potassium ranks as the seventh most abundant element in crustal mineral nutrients and is indispensable for plant growth and development. Consequently, investigating soil nutrients under *Picea schrenkiana* var. *tianschanica* forests is crucial.

Soil total phosphorus and total potassium exhibit strong spatial autocorrelation and are similarly influenced by natural factors such as climate, topography, and soil parent material, which may be related to vegetation heterogeneity or elevation. Dang et al. studied spatial differentiation patterns of soil fertility at different elevations on the southern slope of the Qinling Mountains, revealing that soil organic matter accumulation and transformation processes changed significantly with increasing altitude.

Picea schrenkiana var. *tianschanica* forests in the Tianshan Mountains occupy an important ecological position, yet research on soil nutrient distribution characteristics beneath these forests remains insufficient. Therefore, studying the spatial distribution of soil nutrients under Tianshan spruce forests not only helps reveal how soils support spruce growth but also provides scientific foundations for health evaluation, soil management, and protection measures across different regional forest ecosystems. The primary forest type in the Tianshan Mountains is natural Tianshan spruce forests, which represent valuable forest ecosystems with high biodiversity and unique ecological functions. Soil surveys can help understand soil fertility conditions in these natural forests, providing a basis for protection and management through the development of scientifically sound forest management measures that promote ecosystem health and sustainability.

Previous research on Tianshan spruce forest soils has been limited, particularly concerning soil nutrient variation patterns across elevation gradients. Therefore, this study selected four typical regions along the northern slope of the Tianshan Mountains following the principle of multi-regional and elevation gradient approaches. Sample lines were established within these study areas, and soil samples were collected along elevation gradients to investigate soil nutrient distribution patterns using soil data from four different regions and five elevation gradients. This research is essential for soil nutrient management and health protection of Tianshan spruce forests.

Methods

1.1 Data Acquisition

In 2023, four typical study regions were selected sequentially from east to west along the northern slope of the Tianshan Mountains . All stands were pure *Picea schrenkiana* var. *tianschanica* forests. The study encompassed the mid-eastern Tianshan (Jimsar Division Forest Farm, Eastern Tianshan State-owned Forest Administration), central Tianshan (Xinjiang Agricultural University Internship Forest Farm), mid-western Tianshan (Wusu Division Forest Farm, Eastern Tianshan State-owned Forest Administration), and western Tianshan (Xishan National Nature Reserve within Gongliu County).

Considering the natural growth limits of Tianshan spruce forests (1700–2700 m), sample lines were established in each of the four study regions [Figure 1: see original paper]. The sampling design comprehensively accounted for natural conditions, vegetation distribution, and topographic characteristics to ensure representative sampling points. Within the spruce distribution range, one 30 m × 30 m plot was established every 50 m along elevation gradients, with a total of 75 plots across the four regions. Plots were categorized into five elevation bands: low elevation (1700–1850 m, 15 plots), mid-low elevation (1900–2050 m, 15 plots), mid elevation (2100–2300 m, 15 plots), mid-high elevation (2350–2500 m, 15 plots), and high elevation (2550–2700 m, 15 plots).

Within each plot, soil samples were collected from five points at depths of 0–20 cm and 20–40 cm. Samples were naturally air-dried, uniformly mixed, and brought to the laboratory for processing and analysis. Soil organic matter, total nitrogen, total phosphorus, and total potassium contents were determined using the Walkley-Black dichromate titration method, Kjeldahl digestion method, and nitric acid-perchloric acid digestion method, respectively.

1.2 Data Processing and Analysis

Based on the grading standards for nutrient content from the Second National Soil Survey, soil nutrient contents were graded . Scores were assigned according to grade normalization, with values of 5, 4, 3, 2, and 1 corresponding to grades I, II, III, IV, and V, respectively. The coefficient of variation is an indicator of dispersion degree. When the coefficient of variation is <10%, 10%–100%, and >100%, the variation degree corresponds to weak, moderate, and strong levels, respectively. According to the calculated coefficients of variation for soil nutrients, the weights of soil nutrient indicators were determined using the following formula:

$$W_i = \frac{U_i}{\sum_{k=1}^{n} U_k}$$

where W_i is the weight coefficient for indicator i, U_i is the coefficient of variation value for indicator i, U_k is the coefficient of variation value for indicator k, and

k is the general loop variable for summation. The calculated weights for organic matter, total nitrogen, total phosphorus, and total potassium were 0.29, 0.27, 0.23, and 0.21, respectively.

The soil nutrient content evaluation score for each plot was obtained through weighting and normalized scores using the following formula:

$$\text{SNCI} = \sum_{i=1}^{n} W_i \times X_i$$

where SNCI is the Soil Nutrient Content Index and X_i is the standardized score for health indicator i.

Microsoft Excel 2023 was used to calculate the mean, standard deviation, and coefficient of variation for soil organic matter, total nitrogen, total phosphorus, and total potassium contents. SPSS 26 software was used for significance testing and analysis of variance, while Origin 2024 was used to create various charts and graphs.

Results

2.1 Basic Characteristics of Soil Nutrients Across Regions

The basic soil nutrient conditions across the four regions are presented in . Potassium was the most abundant nutrient element. The highest average organic matter content was observed in mid-eastern Tianshan (111.40 $g \cdot kg^{-1}$), while the lowest was in central Tianshan (90.02 $g \cdot kg^{-1}$). The highest average total nitrogen content was in mid-eastern Tianshan (6.14 $g \cdot kg^{-1}$), and the lowest was in mid-western Tianshan (4.75 $g \cdot kg^{-1}$). The highest average total phosphorus content was in western Tianshan (0.97 $g \cdot kg^{-1}$), and the lowest was in mid-western Tianshan (0.71 $g \cdot kg^{-1}$). The highest average total potassium content was in mid-western Tianshan (28.50 $g \cdot kg^{-1}$), and the lowest was in mid-eastern Tianshan (22.81 $g \cdot kg^{-1}$).

2.2 Distribution Patterns of Soil Nutrients Along Elevation Gradients

The variation of soil nutrient contents with elevation across the four regions is illustrated in [Figure 2: see original paper]. Soil organic matter content showed significant fluctuation trends with elevation, increasing notably within the 1700–2300 m range and reaching maximum values around 2300 m, followed by a clear decreasing trend. The highest content was 185.00 $g \cdot kg^{-1}$ (western Tianshan, 2300 m), while the lowest was 27.20 $g \cdot kg^{-1}$ (western Tianshan, 1700 m).

Soil total nitrogen content showed similar variation trends to organic matter, suggesting strong coupling between these nutrients. The highest total nitrogen content was 12.30 $g \cdot kg^{-1}$ at 2350 m (mid-eastern Tianshan), while the lowest was 1.14 $g \cdot kg^{-1}$ at 1700 m (mid-western Tianshan). Total phosphorus content showed different fluctuation patterns, with a slow increasing trend and relatively gentle fluctuations in mid-eastern and central Tianshan. In mid-western and western Tianshan, an overall trend of initial increase followed by decrease was observed, also with gentle fluctuations. The highest value was 1.41 $g \cdot kg^{-1}$ at 2350 m (western Tianshan), and the lowest was 0.28 $g \cdot kg^{-1}$ at 1700 m (mid-western Tianshan).

Total potassium content showed relatively stable fluctuations overall. In mid-eastern and central Tianshan, an initial increase followed by decrease was observed. In mid-western and western Tianshan, a slight increasing trend with stable conditions was evident. The highest value was 31.60 $g \cdot kg^{-1}$ (mid-western Tianshan, 2400 m), and the lowest was 12.80 $g \cdot kg^{-1}$ (mid-eastern Tianshan, 1700 m).

2.3 Correlation Between Soil Nutrients and Elevation

Correlation analysis between soil nutrient contents and elevation is presented in [Figure 3: see original paper]. Organic matter and total nitrogen contents showed highly significant correlations across all four regions ($P < 0.001$). In mid-eastern Tianshan, elevation showed highly significant correlation with organic matter and total phosphorus contents and significant correlation with total nitrogen and total potassium contents. In central Tianshan, elevation showed highly significant correlation with organic matter, total nitrogen, and total phosphorus contents, but no correlation with total potassium. In mid-western Tianshan, elevation showed weak positive correlation with organic matter and total nitrogen contents, certain correlation with total phosphorus, and highly significant correlation with total potassium. In western Tianshan, elevation showed highly significant correlation with total nitrogen content, significant correlation with organic matter and total phosphorus contents, and weak positive correlation with total potassium.

Overall, elevation demonstrated positive correlation with organic matter, total nitrogen, and total phosphorus contents, particularly pronounced in mid-eastern, central, and western Tianshan. In mid-eastern and mid-western Tianshan, correlations between elevation and total potassium content were highly significant, while in central and western Tianshan these correlations were not significant. All four regions showed highly significant correlations among organic matter, total nitrogen, total phosphorus, and total potassium contents ($P < 0.001$), indicating strong commonality in their formation and fertility development.

2.4 Variability and Differences in Soil Nutrient Content

Analysis of soil nutrient content variability is presented in [Figure 4: see original paper]. In mid-eastern Tianshan, organic matter variability stabilized with increasing elevation, while in central Tianshan, variability was greater in mid-high and high elevation zones. In mid-western Tianshan, variability was greater in mid and mid-high elevation zones, and in western Tianshan, variability was generally large except in mid-low elevation zones. Maximum total nitrogen variability occurred in mid-high elevation zones across all regions, with minimal variability in mid-low, mid, and high elevation zones of mid-eastern Tianshan. Variability was minimal in mid elevation zones of central Tianshan and moderate in other elevations. In mid-western Tianshan, variability was greater in mid-high elevation zones, while in western Tianshan variability was generally moderate.

Total phosphorus content in mid-eastern Tianshan increased with elevation with minimal variability. In central Tianshan, variability tended to be moderate with increasing elevation. In mid-western Tianshan, an increasing trend was observed from low to mid-high elevations, with variability decreasing as elevation increased and increasing in high elevation zones. Western Tianshan showed similar patterns to mid-western Tianshan but with greater overall variability. Total potassium content in mid-eastern and central Tianshan showed a trend of initial decrease followed by increase and then decrease again, while in mid-western and western Tianshan, variability showed a pattern of initial decrease followed by increase, reaching minimum values at mid elevation zones. All four regions showed minimum variability at mid elevation zones.

Analysis of variance results for soil nutrient contents across elevations are presented in . Organic matter content was highest in mid elevation zones, with no significant difference from mid-high elevation zones but significantly higher than low, mid-low, and high elevation zones ($P < 0.05$). Total nitrogen content was highest in mid-high elevation zones, significantly higher than in other zones ($P < 0.05$). Total phosphorus content was highest in mid-high elevation zones, with no significant difference from mid and high elevation zones but significantly higher than low and mid-low elevation zones ($P < 0.05$). Total potassium content was highest in mid-high elevation zones, with no significant difference from mid elevation zones but significantly higher than other zones ($P < 0.05$).

2.5 Evaluation of Soil Nutrient Content Under Spruce Forests

Soil nutrient evaluation scores for plot units are presented in . In mid-eastern and central Tianshan, soil nutrient evaluation scores showed increasing trends with elevation. In mid-western and western Tianshan, scores were highest in mid-high elevation zones and lowest in low elevation zones. Across the four regions, the highest soil nutrient scores occurred in mid-high elevation zones, with no significant differences among regions ($P > 0.05$), but significantly higher than low, mid-low, and high elevation zones ($P < 0.05$).

Based on average scores, within the same region, soil nutrient content rankings from highest to lowest were: mid-high elevation (96.3 points), high elevation (95.5 points), mid elevation (95.0 points), mid-low elevation (88.5 points), and low elevation (79.4 points). Across different regions at the same elevation, soil nutrient rankings from highest to lowest were: western Tianshan (93.4 points), mid-eastern Tianshan (91.4 points), mid-western Tianshan (91.0 points), and central Tianshan (88.0 points).

Discussion

In mountain ecosystems, elevation is a crucial factor influencing differences in soil nutrient content. Xi et al. found that soil nutrient distribution in Tianshan spruce forests varied significantly across different elevation belts, consistent with our research findings. Soil organic matter, total nitrogen, and total phosphorus contents across all four regions accumulated substantially at mid-high elevations, particularly within the 2200–2400 m range, indicating that elevation significantly affects soil nutrient distribution. With increasing elevation, soil organic matter and total nitrogen contents showed clear trends of initial increase followed by decrease, likely related to temperature and moisture changes associated with elevation. Increased soil water content reduces mineralization rates of organic matter and total nitrogen, while low-temperature environments at higher elevations affect soil water infiltration and microbial activity, leading to decreased organic matter and total nitrogen contents.

Different regional climates, soil types, vegetation cover, and biogeochemical processes play key roles in soil nutrient formation and distribution. Under the multiple influences of topography, climate, and vegetation, Tianshan spruce forests exhibit complex variability in soil nutrients, particularly in mid-eastern and western Tianshan where soil organic matter content is high, with this trend being more pronounced in mid-high elevation zones. In contrast, central and mid-western Tianshan show relatively low soil nutrient content, especially in low and mid-low elevation zones where soil nutrient variation shows greater fluctuation. These differences may be related to regional precipitation, temperature, disturbance, and forest management practices. Our findings align with Li et al.'s research on changing trends of soil organic matter and total nitrogen contents with elevation in the Taibai Mountains.

This study confirms that elevation has highly significant correlation with changes in soil organic matter, total nitrogen, and total phosphorus contents, with these nutrients gradually increasing with elevation until reaching peak values followed by decline. This phenomenon indicates a nonlinear relationship between soil nutrient accumulation and elevation, likely influenced by multiple factors. Qin et al. found that although elevation affects soil nutrients, it is not the sole determinant of soil nutrient distribution. In mid-western Tianshan, despite high elevations, soil nutrient variation remained relatively stable, particularly total potassium content, which was hardly affected by elevation changes, indicating that other environmental factors also largely determine soil nutrient distribution. Soil nutrient variability may be influenced by various environmental factors such as seasonal precipitation fluctuations, soil pH, and moisture content differences.

Significant positive correlations among soil nutrients indicate strong coupling relationships among organic matter, total nitrogen, and total phosphorus across different elevations and regions. In mid-eastern and central Tianshan, extremely significant correlations between soil organic matter and total nitrogen and phosphorus suggest that accumulation processes of these nutrients may be interdependent. Soil organic matter, as an important indicator of soil fertility, is closely related to nitrogen and phosphorus release during decomposition, while nitrogen and phosphorus further affect plant growth and soil microbial activity. Although total potassium content showed minimal fluctuation across elevation zones, significant correlations between total potassium and other nutrients in mid-eastern and mid-western Tianshan may be related to soil potassium exchangeability and mineral composition, reflecting relative stability of regional potassium elements.

Our results show that western Tianshan had the highest overall soil nutrient levels, particularly evident in mid-high elevation zones, followed by mid-eastern and mid-western Tianshan, while central Tianshan was relatively nutrient-poor. These differences reflect variations in natural conditions and ecological environments across regions, with higher nutrient accumulation likely associated with superior climatic conditions, while relative nutrient deficiency in central regions may result from climate, terrain, and human disturbance.

Conclusion

1) Elevation significantly affects soil organic matter, total nitrogen, and total phosphorus contents beneath Tianshan spruce forests.

2) Soil organic matter, total nitrogen, and total phosphorus contents show significant positive correlations across elevations, while total potassium content exhibits the most stable distribution across elevations with minimal elevation influence. Overall, soil nutrient content under Tianshan spruce forests on the northern slope of the Tianshan Mountains is relatively abundant, although certain differences and patterns exist across different regions and elevation gradients.

3) Regional soil nutrient content rankings from highest to lowest are: western Tianshan, mid-eastern Tianshan, mid-western Tianshan, and central Tianshan.

4) Elevational soil nutrient content rankings from highest to lowest are: mid-high elevation, high elevation, mid elevation, mid-low elevation, and low elevation.

References

[1] Zhao Huiying, Wang Haiyan. Soil multifunctionality and its driving factors: A review[J]. Chinese Journal of Applied and Environmental Biology, 2024, 30(3): 615-622.

[2] Zhang Zhihua, Zhang Jinhao, Sang Yuqiang, et al. Spatial variations and its influencing factors of soil carbon and nitrogen on the southern foot of Taihang Mountains, China[J]. Chinese Journal of Applied Ecology, 2021, 32(8): 2829-2838.

[3] Li Yuxin, Zhao Xiaomin, Guo Xi, et al. Spatial pattern of soil organic matter in the suburbs of Nanchang City and its influencing factors[J]. Acta Agriculturae Universitatis Jiangxiensis, 2023, 45(3): 749-758.

[4] Jia Lujing, Yang Lian'an, Ji Yongfan, et al. Review on inversion of soil organic matter using satellite remote sensing[J]. Remote Sensing Information, 2023, 38(2): 1-9.

[5] Quan Simao, Wang Xukui, Hu Feng. Changes of soil total nitrogen content in farmland of Jiangsu Province and its influencing factors[J]. Journal of Nanjing Agricultural University, 2018, 41(6): 1078-1084.

[6] Cha Meiqin, Xu Haidong, Cheng Xiangrong, et al. Variations of soil phosphorus form and microbial functional diversity in *Cunninghumia lanceolata-Phoebe bournei* multi-layered mixed plantations of different ages[J]. Acta Ecologica Sinica, 2020, 40(19): 6938-6947.

[7] Wang M, Chen H, Zhang W, et al. Soil nutrients and stoichiometric ratios as affected by land use and lithology at county scale in a karst area, southwest China[J]. Science of the Total Environment, 2018, 619: 1299-1307.

[8] Hu Fang, Lin Qizhong, Wang Qinjun, et al. Quantitative inversion of soil potassium content by using hyperspectral reflectance[J]. Remote Sensing for Natural Resources, 2012(4): 157-162.

[9] Cong Rihuan, Li Xiaokun, Lu Jianwei. Advances in research on influence factors of soil potassium transformation[J]. Journal of Huazhong Agricultural University, 2007, 26(6): 907-913.

[10] Lü Shili, Li Xinping, Li Wenbin, et al. Forest soil nutrient characteristics at different altitudes in Niubeiliang National Natural Reserve[J]. Journal of Northwest A & F University (Natural Science Edition), 2013, 41(4): 161-168, 177.

[11] Zhang Zhonghua, Hu Gang, Zhu Jiedong, et al. Spatial heterogeneity of soil nutrients and its impact on tree species distribution in a karst forest of southwest China[J]. Chinese Journal of Plant Ecology, 2011, 35(10): 1038-1049.

[12] Su Songjin, Liu Jinfu, He Zhongsheng, et al. The spatial heterogeneity of soil nutrients in a mid-subtropical *Castanopsis kawakamii* natural forest[J]. Acta Ecologica Sinica, 2012, 32(18): 5673-5682.

[13] Zhang Jiping, Zhang Linbo, Wang Fengyu, et al. Spatial variation of soil nutrient contents in the Jinggangshan National Nature Reserve[J]. Soils, 2014, 46(2): 262-268.

[14] Dang Kunliang, Dan Wei, Wang Ziquan, Tian Haixia, et al. Spatial distribution and variation pattern of soil fertility at different altitude on south slope in Qinling Mountains[J]. Scientia Silvae Sinicae, 2006, 42(1): 16-21.

[15] Zhang Xibiao, Shangguan Zhouping. Effect of human disturbance on physical properties of soil in artificial *Pinus tabulaeformis* Carr. forests of the Loess Plateau[J]. Acta Ecologica Sinica, 2006, 26(11): 3685-3695.

[16] Xu Xiaoyan, Ma Yijie. K release from potassium containing minerals in soil and its significance for plant nutrition[J]. Chinese Journal of Soil Science, 2001, 32(4): 173-176.

[17] Xi Li, Li Siyao, Xia Xiaoying, et al. Spatial heterogeneity of soil nutrients and environmental interpretation in *Picea schrenkiana* var. *tianschanica* forest[J]. Journal of Central South University of Forestry & Technology, 2022, 42(10): 93-101, 167.

[18] Lou Yanmin, Liu Juanhong, Zhou Xiaoping, et al. Temperature on the viscosity and diffusion coefficient of water[J]. Artificial Intelligence Science and Engineering, 2009, 34(6): 34-39.

[19] Li Dan, et al. Carbon, nitrogen and phosphorus contents in soils on Taibai Mountain and their ecological stoichiometry relative to elevation[J]. Acta Pedologica Sinica, 2017, 54(1): 160-170.

[20] Qin Fucang, Niu Xiaole, Yang Zhenqi, et al. Effects of topographic factors and land use on the spatial variability of soil nutrients in Maoshan Watershed[J]. Journal of Agricultural Science and Technology, 2020, 22(6): 138-148.

[21] Zhang Zhonghua. Ecological research on population and community stability in karst forest vegetation[D]. Shanghai: East China Normal University, 2011.

[22] Li Honglin, Gong Lu, Zhu Meiling, et al. Stoichiometric characteristics of soil in an oasis on northern edge of Tarim Basin, China[J]. Acta Pedologica Sinica, 2015, 52(6): 1345-1355.

[23] Zhang Lei, Zhang Yujuan, Sun Shixian, et al. Effects of different grazing intensity on soil organic carbon content in desert steppe[J/OL]. Acta Agrestia Sinica. [2025-04-14]. http://kns.cnki.net/kcms/detail/11.3362.s.20250410.1506.009.html.

[24] Zhao Xinmiao, Wang Yongming, Zhang Rongfeng, et al. The study of soil nutrients of *Larix principis-rupprechtii* plantations at different altitudes in the northern mountainous of Hebei[J]. Journal of Hebei Agricultural University, 2013, 36(4): 56-61, 81.

[25] Zhang Fuli, Yin Quan, Mao Jianfei, et al. Effects of *Bacillus thuringiensis* transgenic cotton straw returning to field on soil[J]. Chinese Journal of Eco-Agriculture, 2020, 28(5): 734-744.

[26] Tsui C C, Tsai C C, Chen Z. Soil organic carbon stocks in relation to elevation gradients in volcanic ash soils of Taiwan[J]. Geoderma, 2013, 209:

119-127.

[27] Chen L F, He Z B, Du J, et al. Patterns and environmental controls of soil organic carbon and total nitrogen in alpine ecosystems of northwestern China[J]. Catena, 2016, 137: 37-43.

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