# VARIATION CHARACTERISTICS OF FOREST SOIL NUTRIENTS AND THEIR ECOLOGICAL STOICHIOMETRY IN SEJILA MOUNTAINS OF SOUTHEAST TIBET, CHINA

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**Abstract.** Carbon, Nitrogen, Phosphorus, and other nutrient contents and their ecological stoichiometric characteristics of forest soil are helpful to understand soil nutrient cycling pattern in alpine region. The soil samples of six consecutive altitudinal gradients (3800, 3900, 4000, 4100, 4200, and 4300 m) in the northern and southern slopes of Sejila Mountain in southeast Tibet (PR China) was collected in July 2021. The contents of total organic carbon (TOC), total nitrogen (TN), and total phosphorus (TP) were measured, and the ecological stoichiometric values were also calculated. Results showed that altitude had significant effects on N, P, and C/N ($P < 0.05$), slope aspect had extremely significant effects on C, P, C/N, and C/P ($P < 0.01$). Pearson analysis results showed that TOC was significantly positively correlated with TN, N/P, and C/P in the North slope. In the south slope, C/N was negatively correlated with TN and TP. TOC, NiN, and S were positively correlated with soil stoichiometric characteristics. TOC, TN, TP, NiN and slope aspect were the main controlling factors of soil stoichiometric characteristics. The results can provide a theoretical reference for the study of soil nutrient supply and interaction in alpine forest ecosystems.

**Keywords:** *ecological stoichiometry, altitude, slope aspect, Sejila Mountain, Southeast Tibet*

## Introduction

Soil is an extremely important part of terrestrial ecosystems; it is an important support for many ecological processes (Normand et al., 2017) and plays a key role in plant development, which is directly related to the formation, stability, and succession of plant ecological populations (Wardle et al., 2004; Zeng et al., 2017). Scientific researchers generally attach importance to C, N, and P because they are basic nutrients required for the development of organisms (Sterner et al., 2017). These macronutrients are necessary for plant growth and play an important role in growth and metabolism

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processes (Jiang and Xu, 2004). Therefore, C, N, and P in soil nutrient elements are not only the main components of soil, but also important basic elements in plant growth and development, evidently affecting microbial dynamics in soil, decomposition of vegetation litter, food web, and accumulation of soil nutrients with the loop (Elser et al., 2010b; Griffiths et al., 2012). In addition, the dynamics and evolution of soil nutrients are interactive and coupled in ecological processes (Tian et al., 2010; Tao et al., 2016). The study of the variation characteristics of soil nutrient elements in terrestrial ecosystems cannot explain the law of changes in soil quality. Systematically studying the proportional relationship among soil nutrient elements is very important (Zeng et al., 2015a). Therefore, an in-depth study of the ecological stoichiometry of soil nutrients to clarify soil quality, elucidate interactions in soil nutrients, and elucidate soil nutrient availability is important for understanding the cycling and balance mechanisms of soil nutrient elements and the effects of soil nutrient elements in terrestrial ecosystems. The degree of influence of plant community structure and function is significant (Zeng et al., 2015a; Zechmeister-Boltenstern et al., 2015; Yang et al., 2015), and slope aspect and altitude may also be the main factors that directly affect the content and distribution of these soil elements.

Ecological stoichiometry focuses on the balance of various chemical nutrients in ecological interactions (Elser et al., 2000). Many studies have used regional or global patterns of plant tissue stoichiometry to indicate vegetation composition, dynamics, and nutrient limitations (Güsewell, 2004; Reich and Oleksyn, 2004; Han et al., 2005; Yuan et al., 2011). One study showed that in forest ecosystems, the global carbon–nitrogen stoichiometric ratio changes over time (Yang and Luo, 2011). Scientists have also investigated how C, N, and P stoichiometry in soil modulates vegetation patterns (Bui and Henderson, 2013). The C:N:P ratio in the soil directly expresses the degree of soil fertility and indirectly indicates the nutritional status of plants (Wang and Yu, 2008; Elser et al., 2010a; Batjes, 2014). Jiang et al. (2011) deeply studied the mulching conditions of herbs, shrub plants, and trees in Qilian Mountains. The complex coupling relationship among C, N, and P elements in soil has a good guiding significance for the study of soil nutrient supply status and element cycle. Ratio characteristics indicate the soil ecological stoichiometric characteristics. Thus far, research results on the C, N, and P values and their ecological stoichiometric characteristics of forest soils in China’s alpine mountains are few, thereby limiting the researchers’ understanding of the soil trace element cycle laws in this special ecological region. Chemometrics provides a framework to analyze such research.

Tibet has a special geographical location in China. It is the main body of the Qinghai–Tibet Plateau and an important ecological protection barrier. It is also a region with a very unique relationship between ecology and the environment in the world (Kumar, 2017). It is a good natural laboratory for studying Chinese forest soil. Different altitudes create differences in natural temperature difference, air humidity, and light radiation, thereby becoming an important area for studying forest soil. Another characteristic of high mountains is their slope aspect. Plants with different slope aspects have different environmental impacts on the plant ecosystem due to the difference in exposure to Sunlight, irradiation and rainfall. Studying the soil characteristics of different slopes can evaluate the influence of different light and water conditions on the soil and vegetation of the mountain. At the same time, the environmental factors of different slopes are different; thus, the soil shows differences, resulting in different altitudes of different slopes. Differences in soil C, N, and P contents at height were found, affecting the ecological stoichiometric characteristics of soil C, N, and P contents. Thus far, studies on the ecological stoichiometric characteristics of soil C, N, and P content are abundant, but reports on the comprehensive research on the ecological stoichiometric characteristics of soil CNP content in Sejila Mountain are limited. The distribution characteristics of soil nutrient content of TOC, TN, and TP, as well as the ratio of TOC content to TN content (C/N), and the relationship between TOC content and TP content were studied, considering the forest soils of different slopes and altitudes in the Sejila Mountains in southeastern Tibet as the research object. Ecological stoichiometric characteristics, such as the ratio of TP content (C/P), the ratio of TN content to TP content (N/P), are studied to further reveal the ecological stoichiometric characteristics of C, N, and P in forest ecosystem soils in alpine regions of China and provide theoretical support for the study of soil–plant system material cycle and nutrient supply. Therefore, this study aimed to:(1) explore the distribution characteristics of soil C, N, P and their stoichiometric indicators along altitudinal gradients in Sejila Mountain of southeast Tibet, China; (2) determine the main influencing factors on ecological stoichiometric characteristics of C, N, and P in Sejila Mountains.

## Materials and methods

### *Overview of study area*

Sejila Mountain is located in Nyingchi City (94°28′–94°51′E, 29°21′– 29°50′N) in the southeastern part of Tibet, China. It is located in the middle and lower reaches of the Yarlung Zangbo River and belongs to the remnants of the Nyainqentanglha Mountains; the altitude is in the area of 2200–5300 m. Affected by the warm and humid monsoon of the Indian Ocean, this area is a typical subalpine temperate semi-humid climate zone, with rich and diverse vegetation types, and evident vertical zonality of the mountain. Subalpine includes cold temperate dark coniferous forest, pine forest, deciduous broad-leaved forest, and mountain temperate coniferous and broad-leaved mixed forest (Zhu et al., 2020; Zhang et al., 2022).

The average temperature throughout the year is approximately −0.73 °C, the highest average temperature in July is 9.23 °C, and the lowest average temperature in January is −13.98 °C. The extreme minimum temperature is −31.6 °C, the extreme maximum temperature is 24.0 °C, the annual average sunshine duration is 1150.6 h, the sunshine percentage is 26.1%, the maximum sunshine duration is December (151.7 h), the sunshine percentage is 40%, and the annual average relative humidity is 78.83%. The annual average precipitation is 1134.1 mm, and the evaporation is 544.0 mm, accounting for 48.0% of the annual average precipitation. The rainy season is from June to September, accounting for 75%–82% of the annual rainfall, of which August has the most rainfall, with an average of 294.2 mm, accounting for 30% of the annual rainfall. The soil types are mostly mountain brown soil and acid brown soil, with a pH value of 4–6, an average thickness of 60 cm, and an insignificant degree of humus (Zhu et al., 2020; Zhang et al., 2022).

### *Experimental design and sample determination*

Samples were obtained from six consecutive altitude gradients of 3800, 3900, 4000, 4100, 4200, and 4300 m on the north and south slopes in July 2021, and three 10 m × 10 m plots were set up in each elevation gradient in Sejila Mountain (*Fig. 1*) of southeast Tibet. The basic information of the sampling plot was shown in *Table 1*. In the five-point sampling method, 0–20 cm of soil was collected and mixed evenly after peeling off the surface litter and humus layer of each sample point, and finally the soil sample was reduced to 1 kg by the quartering method to obtain the soil sample for testing. The sample point, altitude, soil type, and other information are recorded (Wu et al., 2019a). Six elevations, two slope aspects, three plots for each elevation, and three replicates for each plot were found, for a total of 108 scattered soil samples. After all soil samples were collected, non-soil components, such as animal and plant residues, gravel, and intrusions, were immediately removed, and then divided into two parts; they were placed into Ziploc bags and returned to the laboratory, sealed, and stored in a refrigerator at 4 °C and used for soil determination. Total organic carbon (TOC) was measured by $K_2Cr_2O_7$ external heating method (Bao, 2000). Kjeldahl method was developed to determine total nitrogen (TN) (Bao, 2000). Nitrate nitrogen ($NO_3^-$-N, NiN) and Nitrite nitrogen ($NO_2^-$-N, NaN) was determined by the phenol disulfonic acid colorimetry method (Haby, 1989). Ammonium nitrogen ($NH_4^+$-N, AmN) was extracted with 1.2 mol/L KCl via the indophenol blue colorimetric method (Dorich and Nelson, 1983). Particulate organic carbon (POC) was assayed using the method of Garten et al. (1999). Easily oxidized organic carbon (EOC) was assessed using the determination method of Chen et al. (2017). Dissolved organic carbon (DOC) was determined using the method of Fang et al. (2014). Soil total phosphorus (TP) was determined by $HClO_4$-$H_2SO_4$ digestion combined with molybdenum antimony resistance spectrophotometric method, soil available phosphorus (AP) was determined by molybdenum antimony method after 0.5 M $NaHCO_3$ extraction, soil total potassium (TK) was determined by HF-$HClO_4$ digestion combined flame spectrum method, and soil available potassium (AK) was determined by flflame spectrum method after extraction with 1 M $NH_4OAc$ (Bao, 2000).

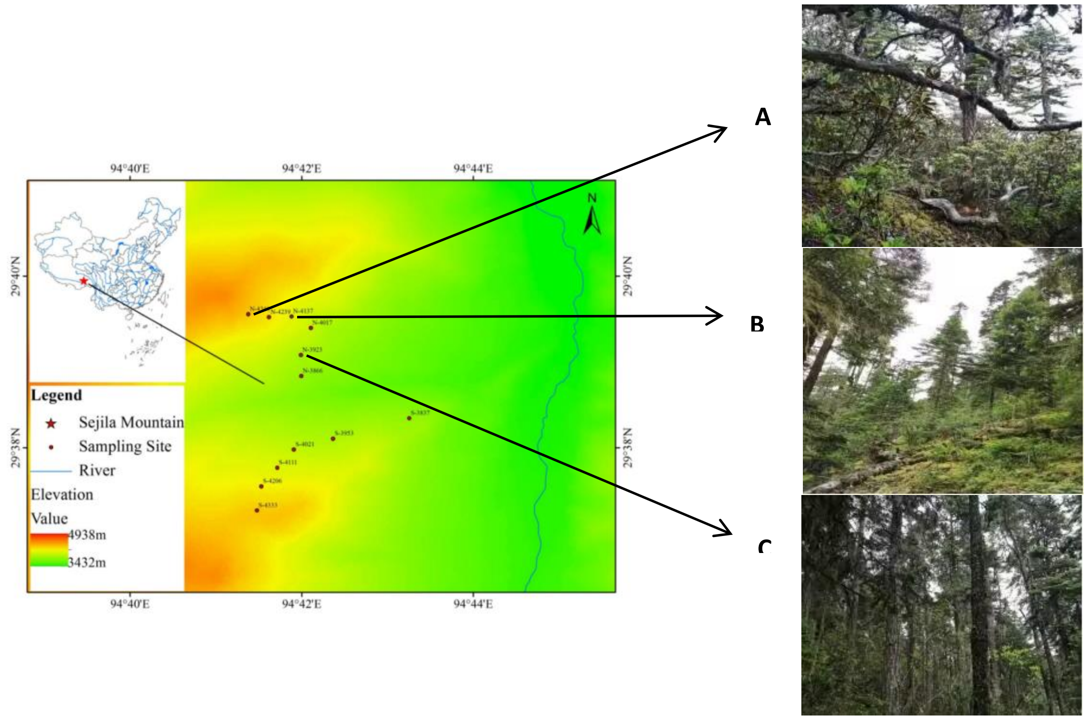

***Figure 1.*** *Location of sampling sites. Three photos of sampling plots in (A) 4348 m, (B) 4137 m and (C) 3923 m in north slope*

***Table 1.** Basic information of the sampling plots*

| **Alt (m)** | **Northern slope** | | | | | **Southern slope** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Long. (°E)** | **Lat. (°N)** | **Average coverage** | **Average crown density** | **Litter thickness (cm)** | **Long. (°E)** | **Lat. (°N)** | **Average coverage** | **Average crown density** | **Litter thickness (cm)** |
| 3800 | 94.71 | 29.64 | 0.87±0.02 | 0.67±0.05 | 12.00±2.65 | 94.72 | 29.64 | 0.91±0.03 | 0.61±0.02 | 9.00±1.00 |
| 3900 | 94.71 | 29.64 | 0.66±0.04 | 0.52±0.03 | 9.00±1.73 | 94.71 | 29.64 | 0.78±0.02 | 0.67±0.02 | 13.00±4.00 |
| 4000 | 94.71 | 29.65 | 0.87±0.04 | 0.46±0.04 | 14.33±3.21 | 94.71 | 29.64 | 0.95±0.02 | 0.51±0.02 | 19.33±4.51 |
| 4100 | 94.71 | 29.65 | 0.86±0.04 | 0.61±0.03 | 10.33±2.52 | 94.70 | 29.63 | 0.87±0.02 | 0.45±0.04 | 15.33±2.52 |
| 4200 | 94.70 | 29.65 | 0.78±0.04 | 0.49±0.03 | 6.33±1.53 | 94.70 | 29.63 | 0.93±0.03 | 0.65±0.04 | 14.67±2.08 |
| 4300 | 94.70 | 29.65 | 0.69±0.04 | 0.46±0.02 | 14.67±3.06 | 94.70 | 29.63 | 0.71±0.03 | 0.41±0.02 | 17.67±4.51 |

Mean ± standard deviation (SD). Alt., altitude; Long., longitude; Lat., latitude

### *Data analysis*

Excel software was used for preliminary data processing. All the statistics were calculated using SPSS software (v.25.0, IBM Corp., Armonk, NY, United States) and plotting was performed on Origin 2021b (Origin lab, Northampton, Massachusetts,

United States). One-way ANOVA and least significant difference method (LSD) were used to analyze the significance of the differences in TOC, TN, TK, and TP contents in different slope directions at different altitudes. A $p$-value $< 0.05$ was considered for assessing significant statistical effects. The independent sample T test (Student-t test) was used to test the difference in soil measurement parameters in different slope aspects at the same altitude, and origin mapping was used. The degree of spatial variation of each indicator in soil was expressed by coefficient of variation (CV). When the CV was 0–10%, 10%–100%, and > 100%, it had weak, medium, and strong variation, respectively (Cambardella et al., 1994). Redundancy analysis method (RDA) was used to intuitively express the relationship between soil C, N, and P ecological stoichiometric characteristics and soil factors. C/N, C/P, and N/P were used as species variables, and the 12 soil factors (TOC, TN, TP, TK, AmN, NiN, NaN, AK, AP, DOC, EOC, and POC) are used as environmental variables. Redundancy analysis (RDA) was performed using Canoco 5.0 (Microcomputer Power, United States).

All abbreviations of indicators used in this study are described in *Table 2*.

***Table 2.** The definition, abbreviation, and units for indicators used in the present study*

| **Parameter** | **Definition** | **Unit** |
|---|---|---|
| TOC | Total organic carbon | g/kg |
| TN | Total nitrogen | g/kg |
| TP | Total phosphorus | g/kg |
| TK | Total kalium | g/kg |
| AP | Available phosphorus | mg/kg |
| AK | Glucose concentration | g/kg |
| EOC | Easily oxidized organic carbon | mg/kg |
| POC | Particulate Organic Carbon | g/kg |
| DOC | Dissolved organic carbon | mg/kg |
| AmN | Ammonium nitrogen | mg/kg |
| NaN | Nitrate nitrogen | mg/kg |
| NiN | Nitrite nitrogen | mg/kg |
| Alt | Altitude | m |
| SA | Slope aspect | |

## Results

### *Soil C, N, P, and ecological stoichiometric characteristics of Sejila Mountains*

The distribution patterns of soil C, N, and P contents and their ecological stoichiometry with elevation are shown in *Figure 2* and *Tables 3* and *4*. TOC content on the north slope is basically stable with elevation, while on the southern slope it increased with elevation ($P = 0.046$, $R^2 = 0.347$). The maximum TOC value occurs at 4300 m on the north slope (53.07 ± 23.29 g/kg) and at 4200 m on the south slope (76.31 ± 25.52 g/kg). The results of ANOVA showed that elevation had no significant effect on TOC content, and slope direction had a very significant effect on it ($P < 0.01$); On both two slopes, TN content increased with elevation (North slope: $P = 0.043$, $R^2 = 0.213$; South slope: $P = 0.039$, $R^2 = 0.211$), there was no significant difference among altitudinal gradients and between the slope aspects ($P > 0.05$). The characteristics of TP with elevation showed clear opposite trends on both slopes, increasing significantly with elevation on the northern slope ($P = 0.047$, $R^2 = 0.185$), but decreasing significantly with elevation on the southern slope ($P = 0.042$, $R^2 = 0.166$), Maximum (0.72 ± 0.07 g/kg) at 3900 m in north slope and maximum at 3800 m in south slope (0.63 ± 0.05 g/kg); Altitude had a significant effect on TP ($P < 0.05$), slope direction had a very significant effect on TP ($P < 0.01$), and altitude and slope direction had a very significant interactive effect on ($P < 0.001$); C/N only increased significantly with altitude on the southern slope ($P = 0.047$, $R^2 = 0.381$), Both elevation and slope aspect had significant effects on C/N ($P < 0.01$; $P < 0.001$), the combined effect of elevation and slope aspect had significant influence on C/N ($P < 0.05$).; C/P increased with elevation (North slope: $P = 0.049$, $R^2 = 0.191$; South slope: $P = 0.046$, $R^2 = 0.133$), Elevation had no significant effect on C/P ($P > 0.05$), however, slope had a very significant effect on it ($P < 0.001$), and elevation and slope aspect had significant interactive effect on C/P ($P < 0.05$); N/P increased significantly with elevation on the northern slope ($P = 0.045$, $R^2 = 0.173$), but decreased significantly with altitude on the southern slope ($P = 0.038$, $R^2 = 0.162$).

***Table 3.*** *Multiple comparisons of soil carbon, nitrogen and phosphorus ecological stoichiometry with different slope aspects and elevations*

| Aspect | Altitude/m | Indicators | | | | | |
|---|---|---|---|---|---|---|---|
| | | **TOC (g/kg)** | **TN (g/kg)** | **TP (g/kg)** | **C/N** | **C/P** | **N/P** |
| North slope | 3800 | 45.82 ± 7.49Aa | 2.21 ± 0.44Aa | 0.42 ± 0.08Ab | 20.87 ± 2.29Aa | 109.30 ± 3.68Ba | 5.28 ± 0.61Aa |
| | 3900 | 52.86 ± 9.25Aa | 3.55 ± 0.84Aa | 0.72 ± 0.07Aa | 15.03 ± 1.13Ab | 72.07 ± 5.83Ba | 4.83 ± 0.72Aa |
| | 4000 | 38.29 ± 3.07Ba | 2.78 ± 0.17Aa | 0.58 ± 0.03Bab | 13.73 ± 0.51Abc | 65.24 ± 3.27Aa | 4.75 ± 0.28Aa |
| | 4100 | 34.52 ± 5.59Ba | 2.73 ± 0.87Aa | 0.52 ± 0.02Ab | 13.27 ± 3.26Abc | 66.64 ± 13.44Aa | 5.28 ± 1.81Aa |
| | 4200 | 45.67 ± 3.09Ba | 4.08 ± 0.13Aa | 0.71 ± 0.11Aa | 13.17 ± 3.26Ac | 66.64 ± 13.44Ba | 5.28 ± 1.81Aa |
| | 4300 | 53.07 ± 23.29Aa | 3.96 ± 2.15Aa | 0.58 ± 0.04Bab | 13.82 ± 1.32Abc | 89.31 ± 33.41Aa | 6.65 ± 3.17Aa |
| South slope | 3800 | 47.14 ± 15.78Aa | 2.19 ± 1.04Aa | 0.63 ± 0.05Ba | 22.55 ± 3.91Ab | 76.00 ± 32.59Aa | 3.57 ± 2.01Ab |
| | 3900 | 59.55 ± 7.83Aa | 1.98 ± 0.55Aa | 0.38 ± 0.14Bb | 32.02 ± 11.03Ba | 171.32 ± 74.17Aa | 5.26 ± 0.82Aab |
| | 4000 | 64.84 ± 9.32Aa | 3.89 ± 0.56Aa | 0.56 ± 0.04Aa | 16.66 ± 0.25Bb | 114.99 ± 25.34Ba | 6.91 ± 1.54Aa |
| | 4100 | 62.44 ± 5.39Aa | 3.20 ± 0.54Aa | 0.55 ± 0.03Aa | 19.75 ± 2.38Ab | 113.08 ± 10.29Ba | 5.76 ± 0.65Aab |
| | 4200 | 76.31 ± 25.52Aa | 4.20 ± 1.51Aa | 0.57 ± 0.04Aa | 18.46 ± 2.41Ab | 132.25 ± 41.92Aa | 7.32 ± 2.63Aa |
| | 4300 | 54.34 ± 14.38Aa | 3.13 ± 1.15Aa | 0.40 ± 0.08Ab | 17.83 ± 2.05Ab | 131.93 ± 7.57Ba | 7.49 ± 1.24Aa |
| Two-way ANOVA | AL | $0.994^{ns}$ | $2.715^{ns}$ | 2.931* | 5.751** | $1.144^{ns}$ | $2.158^{ns}$ |
| | SA | 13.231** | $0.136^{ns}$ | 8.349** | 26.801*** | 21.106*** | $1.301^{ns}$ |
| | AL×A | $1.757^{ns}$ | $1.365^{ns}$ | 10.111*** | 3.175* | 3.281* | $0.991^{ns}$ |
| | Residuals | 2.453 | 1.867 | 6.687 | 6.495 | 3.931 | 1.551 |

The representative factor has no significant effect on the index; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$. Different uppercase letters represented significant differences in slope aspects ($P < 0.05$). Different lowercase letters represent significant differences between different altitudes in the same slope aspect ($P < 0.05$)

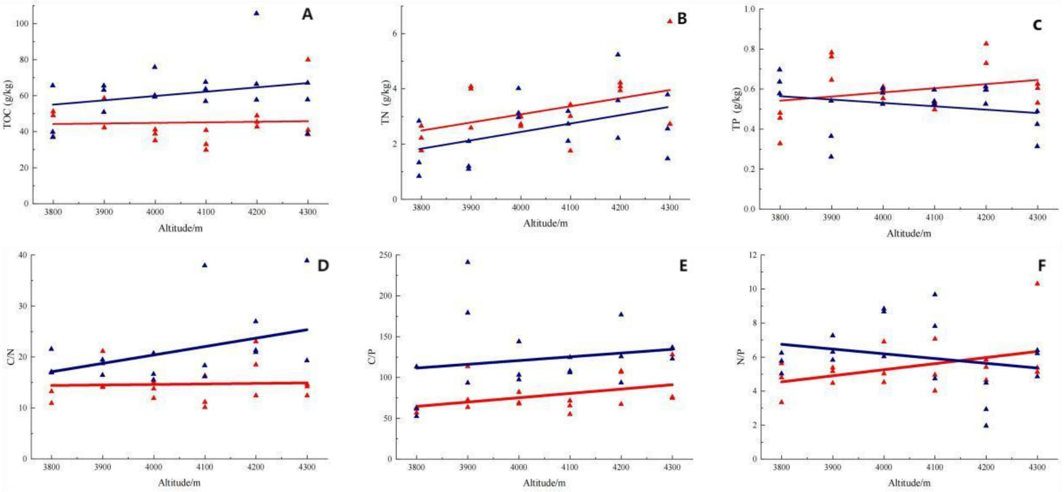

***Figure 2.*** *Distribution characteristics of soil carbon, nitrogen and phosphorus ecological stoichiometry along altitudinal gradient. The red line represents the North Slope; The blue line represents the southern slope*

## *Relationships among soil C, N, P, and their stoichiometric characteristics in Sejila Mountains*

The results of Pearson correlation analysis indicate that, on the northern slope, TOC was significantly positively related with TN ($r = 0.805$, $P < 0.001$), N/P ($R = 0.686$, $P = 0.002$), and C/P ($R = 0.603$, $P = 0.008$); TN was significantly positively related with N/P ($R = 0.805$, $P < 0.001$), but significantly negatively related with C/N ($R = -0.606$, $P = 0.008$); C/N was significantly positively related with C/P ($R = 0.498$, $P = 0.007$), but significantly negatively related with TP ($R = -0.545$, $P = 0.019$) (*Fig. 3A*). On the southern slope, TOC was significantly positively correlated with TN ($R = 0.810$, $P < 0.001$) and N/P ($R = 0.769$, $P < 0.001$); C/N was significantly negatively related with TN ($R = -0.669$, $P = 0.002$) and TP ($R = -0.509$, $P = 0.031$); TN was significantly positively correlated with N/P ($R = 0.833$, $P < 0.001$) (*Fig. 3B*). The specific relationship between soil CNP content and their stoichiometric ratio could be fitted with a binomial model (*Fig. 4; Table 5*). On the northern slope, the relationship between TN and C/N can be expressed as follows: $y = 32.056\text{-}8.4143x + 0.8407x^2$ ($P = 0.001$, $R^2 = 0.569$); the relationship between TOC and C/P was as follows: $y = 68.1133-0.4972x + 0.0148x^2$ ($P = 0.026$, $R^2 = 0.382$); the relationship between TP and C/P was: $y = 217.2196-401.1152x + 268.9503x^2$ ($P = 0.007$, $R^2 = 0.284$); the relationship between TN and N/P was: $y = 5.2082-0.8x + 0.2426x^2$ ($P < 0.001$, $R^2 = 0.737$). On the southern slope, the relationship between TN and C/N can be expressed as follows: $y = 50.239-15.4628 + 1.7368x^2$ ($P < 0.001$, $R^2 = 0.621$), the relationship between TN and N/P was: $y = 5.2082-0.8x + 0.2426x^2$ ($P < 0.001$, $R^2 = 0.696$); the relationship between TP and N/P was: $y = 3.4394 + 7.1539x-6.1290x^2$ ($P = 0.027$, $R^2 = 0.381$).

## *Influencing factors on ecological stoichiometric characteristics of C, N, and P in Sejila Mountains*

The bi-sequence diagram of soil stoichiometric ratio and environmental variables can be obtained by analyzing the relationship between the two groups of variables (*Fig. 5*).

RDA results showed that the soil factors explained 55.54% and 39.54% of the soil stoichiometric ratios on axes 1 and 2 of the ordination diagram, respectively (*Table 6*). The accumulation explanation rate of the first two axes was 95.08%, which indicated that the axis can effectively reflect the relationship between soil stoichiometric ratio and soil factors and was mainly determined by the first axis. *Figure 3* shows that the included angles of TOC, NiN, S, and the three soil stoichiometric ratios were less than 90°, showing a positive correlation; whereas the included angle of TP, TK, AP, DOC, and the three soil chemical ratios was > 90°, showing a negative correlation. The importance of each soil factor was further studied, and the Monte Carlo test was performed for each soil factor (*Table 7*). TN contributed most to soil stoichiometric characteristics (contribution rate: 42.9%) and had significant correlation ($P < 0.01$). The second contributor was TOC (contribution rate: 36.2%). TP and NiN also had significant effects on C/N, C/P, and N/P, and their contribution rates were 17.7% ($P = 0.002$) and 1.6% ($P = 0.004$). The total contribution of the four soil factors reached 98.4%.

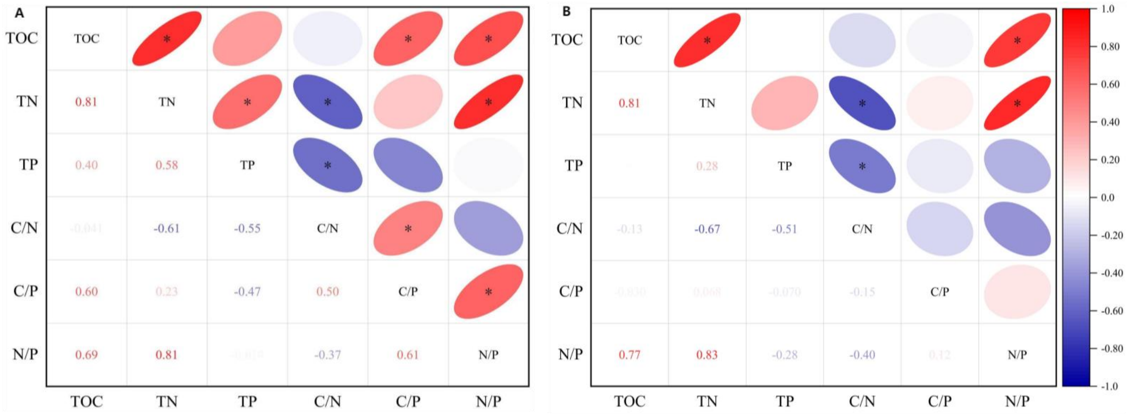

***Figure 3.*** *Correlation analysis between soil C, N and P contents and stoichiometric ratio; (A) north slope;(B) south slope*

## Discussion

### *Soil C, N, and P contents and their ecological stoichiometric characteristics in Sejila Mountains*

Although altitude did not have a significant effect on soil TOC content, it remained stable on the northern slope and increased on the southern slope, consistent with the results of He et al. (2015). From the perspective of different slopes, the TOC content of the southern slope was much higher than that of the northern slope, and reached the maximum value at 4200 m. The higher plant coverage and sufficient soil moisture on the southern slope strengthen the soil nutrient retention, and the TOC decomposition rate slowly accumulates (Zhu et al., 2013a). The content of TN in the northern and southern slopes increased with elevation, consistent with the results of Liu et al. (2016), and the content in the northern slope was much richer. Previous studies have shown that on the northern slope, soil nitrogen uptake increased due to the degradation of litter, the action of nitrogen-fixing microorganisms, and the accumulation of combined nitrogen from precipitation (Kong et al., 2009; Zhong and Xin, 2004; Chen et al., 2022).

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***Table 4.*** *Regression analysis of ecological stoichiometric characteristics of soil carbon, nitrogen and phosphorus*

| **Aspect** | **Regression analysis** | **TOC** | **TN** | **TP** | **C/N** | **C/P** | **N/P** |
|---|---|---|---|---|---|---|---|
| North slope | Equation | $y=0.0031x+32.437$ | $y=0.0029x-8.6744$ | $y=0.0002x-0.246$ | $y=0.001x+10.5559$ | $y=0.0529x-136.7273$ | $y=0.0035x-9.032$ |
| | $R^2$ | 0.002 | 0.213 | 0.185 | 0.002 | 0.191 | 0.173 |
| | P | 0.853 | 0.043 | 0.047 | 0.839 | 0.049 | 0.045 |
| South slope | Equation | $y=0.0239x-36.2503$ | $y=0.003x-9.2156$ | $y=1.2035-0.0001x$ | $y=0.0164x-45.5835$ | $y=0.0458x-62.4526$ | $y=17.3536-0.0027x$ |
| | $R^2$ | 0.374 | 0.211 | 0.166 | 0.381 | 0.133 | 0.162 |
| | P | 0.046 | 0.039 | 0.042 | 0.047 | 0.046 | 0.038 |

***Table 5.*** *Regression analysis of soil carbon, nitrogen and phosphorus with stoichiometric characteristics*

| **Aspect** | **Regression analysis** | **C-C/N** | **N-C/N** | **C-C/P** | **P-C/P** | **N-N/P** | **P-N/P** |
|---|---|---|---|---|---|---|---|
| North slope | Equation | $y=7.5826+0.2936x-0.0028x^2$ | $y=32.056-8.4143x+0.8407x^2$ | $y=68.1133-0.4972x+0.0148x^2$ | $y=217.2196-401.1152x+268.9503x^2$ | $y=5.2082-0.8x+0.2426x^2$ | $y=3.4394+7.1539x-6.1290x^2$ |
| | $R^2$ | 0.027 | 0.569 | 0.382 | 0.284 | 0.737 | 0.007 |
| | P | 0.809 | 0.001 | 0.026 | 0.007 | $p < 0.001$ | 0.948 |
| South slope | Equation | $y=22.6803+0.0053x-0.0004x^2$ | $y=50.239-15.4628+1.7368x^2$ | $y=130.3079-0.1429x+0.0004x^2$ | $y=107.7312+107.8894x-143.1207x^2$ | $y=2.235+1.03x+0.057x^2$ | $y=-7.1160+66.62686x-75.8408x^2$ |
| | $R^2$ | 0.017 | 0.621 | 0.001 | 0.081 | 0.696 | 0.381 |
| | P | 0.877 | $p < 0.001$ | 0.993 | 0.947 | $p < 0.001$ | 0.027 |

***Table 6.*** *Eigenvalues and cumulative interpretation ranking of soil stoichiometric*

| **Axis sequence** | **Axis 1** | **Axis 2** | **Axis 3** | **Axis 4** |
|---|---|---|---|---|
| Soil stoichiometric ratio characteristic value | 0.5554 | 0.3954 | 0.0018 | 0.0372 |
| Correlation between soil stoichiometric ratio and soil physicochemical factors | 0.9748 | 0.9829 | 0.54 | 0 |
| Soil stoichiometric ratio cumulative interpretation | 55.54 | 95.09 | 95.27 | 98.99 |
| Soil stoichiometric ratio - the cumulative amount explained by soil physicochemical factors | 58.3 | 99.81 | 100 | |

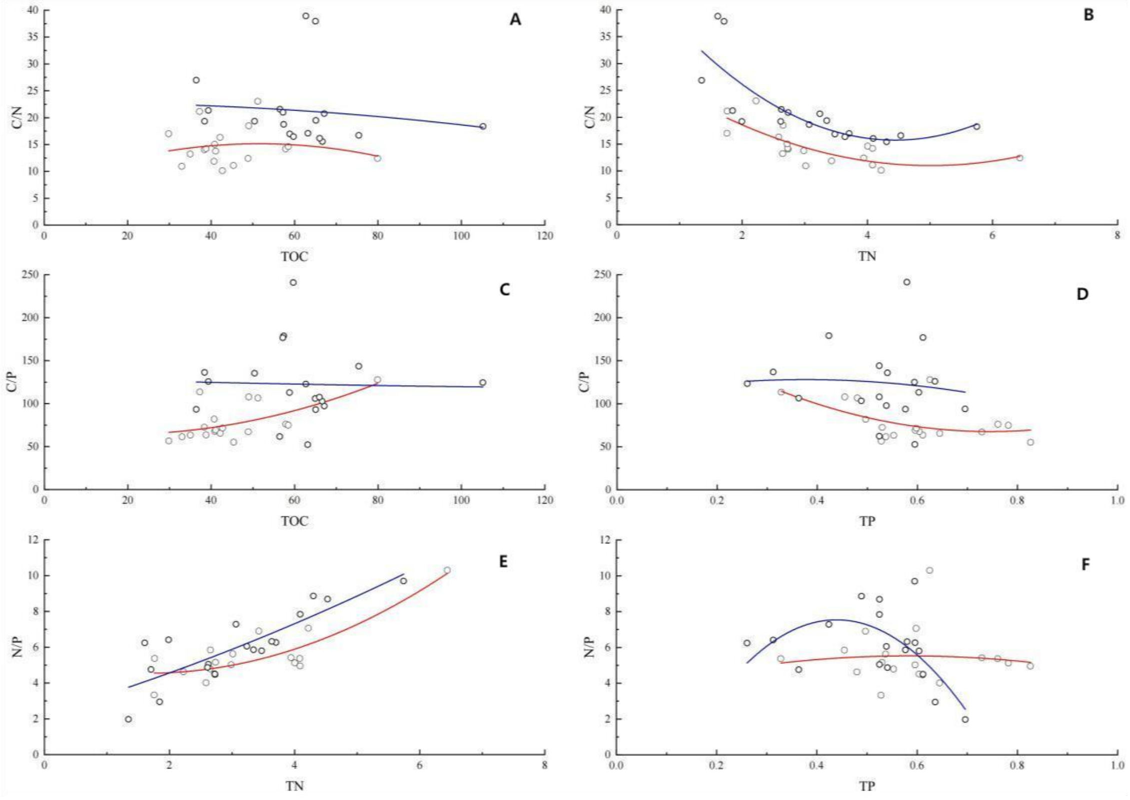

***Figure 4.*** *Fitting analysis of soil nutrient content and stoichiometric characteristics*

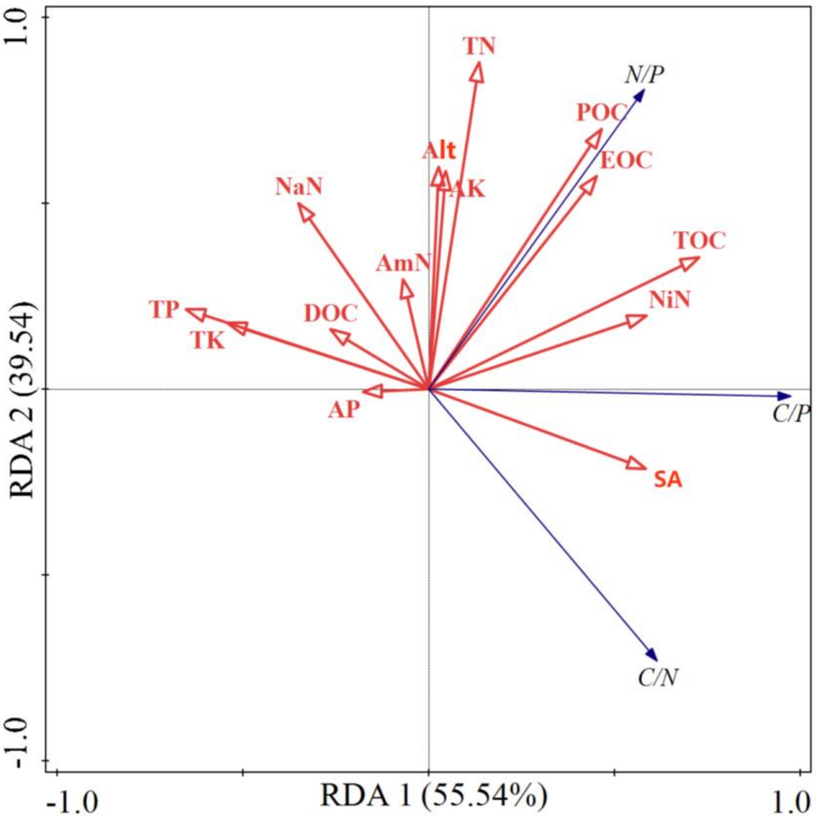

***Figure 5.*** *Redundancy analysis of soil stoichiometric ratio and soil physicochemical factors*

***Table 7.*** *The importance ranking and significance test results of soil physical and chemical factor variable explanation*

| Environmental factors | Explain/% | Contribution/% | Importance-F | Significant-P |
|---|---|---|---|---|
| TP | 16.9 | 17.7 | 70.1 | 0.002 |
| TN | 40.9 | 42.9 | 55 | 0.002 |
| TOC | 34.5 | 36.2 | 17.9 | 0.002 |
| NiN | 1.5 | 1.6 | 7.6 | 0.004 |
| EOC | 0.3 | 0.3 | 1.7 | 0.172 |
| S | 0.2 | 0.2 | 1.2 | 0.284 |
| NaN | 0.2 | 0.2 | 1.1 | 0.284 |
| AK | 0.2 | 0.2 | 0.8 | 0.39 |
| TK | 0.2 | 0.2 | 0.8 | 0.47 |
| AmN | <0.1 | 0.1 | 0.5 | 0.602 |
| POC | <0.1 | <0.1 | 0.4 | 0.606 |
| AP | <0.1 | <0.1 | 0.3 | 0.714 |
| AL | <0.1 | <0.1 | 0.3 | 0.734 |
| DOC | <0.1 | <0.1 | 0.2 | 0.822 |

C/N is a sensitive index of soil quality, and it affects the cycling of soil nutrients, organic C, and N (Luo et al., 2015; Zhu et al., 2013b). Studies have shown that C/N content on the southern slope increases along with elevation, probably due to the decrease in temperature and increase in humidity in the forest, the inhibition of soil microbial activity, the decrease in soil carbon mineralization rate, and the increase in soil organic carbon accumulation (Qin et al., 2019; Fang et al., 2004). In the northern slope, TOC content increased or changed slightly with the increase in elevation gradient, and the change in soil TOC content was less than that of TN content. The reason may be that extra N elements required for microbial growth in the soil would be released into the soil and increase its N element content (Ma et al., 2020; Wang et al., 2020; Hou et al., 2021; Lasota and Bońska, 2021; Li et al., 2021). The variation range of TOC content was larger than that of TN content, the C/N value was higher than the average level of Chinese forest soil (13.7) (Wu et al., 2019b), and TOC was at an abundance level. According to the principle of ecological stoichiometry, the formation of organic matter also requires a certain amount of N and some other nutrients (Tao et al., 2016; Zhu et al., 2013b). Therefore, stable C/N can be used to estimate soil N stocks, C stocks, and C and N cycling in ecosystems (Tao et al., 2016; Tessier and Raynal, 2003). Soil C/P was regarded as the standard of soil P mineralization ability, and it was also the basic index to evaluate the P release amount of soil organic matter and the ability of microorganisms to absorb P in the environment after mineralization (Zeng et al., 2015b). The present study has shown that the soil C/P value in the northern and southern slopes increased with altitude, but no significant difference was found between the altitudes. Low soil C/P value represented high availability of soil P, which can promote soil microorganisms to decompose organic matter and release nutrients, as well as increase the content of soil available P (Tian et al., 2010; Griffiths et al., 2012). At the same time, we found that the soil C/P values of the six sampling points of each elevation in both slopes were lower than the average in China except for the southern slope at an altitude of 3800 m, which was higher than the average in China (136) (Tian et al., 2010; Wu et al., 2003), but much lower than the global average (186) (Zhao et al., 2015a). N/P can be used as an indicator of soil nitrogen saturation status and a threshold for measuring the degree of soil nutrient limitation (Zhao et al., 2015b). In this study, the soil N/P value increased along the elevation in the northern slope, whereas the trend in the southern slope was opposite; no significant difference was found between elevations. The mean soil N/P values of the six elevation gradients on both slopes of Sejila Mountains were much lower than the global average (13.1) and the Chinese average (9.3) (Wu et al., 2003; Zhao et al., 2015a). The CV range of N/P was 5.86%–56.90%, combined with the higher C/P value, which indicates a possibility that soil N and soil P was relatively deficient in alpine forest ecosystems of Sejila Mountains (Cleveland and Liptzin, 2007; Tessier and Raynal, 2003; Bui and Henderson, 2013; Tian et al., 2018). Soil C/N and N/P showed two opposite trends with elevation. Soil C/N increased with the elevation on the southern slope, but decreased with the elevation on the northern slope; soil N/P decreased with the elevation on the southern slope and increased with the elevation on the northern slope. Meanwhile, the soil TN content in the study area was extremely high; it was higher than the national average soil nitrogen content (1.07) (Liu et al., 2022). The variations of soil C:N and N:P along the elevation gradient were mainly restricted by N element.

### *Relationships between soil C, N, and P stoichiometric characteristics and soil factors*

Soil ecological stoichiometric characteristics are not only affected by vegetation, climate, topography, and other factors, but also closely related to soil physical and chemical properties (Zhang, 2017). The carrier and medium for plants to absorb nutrients come from soil, which is also an important site for a series of physiological and biochemical reactions; changes in soil physical and chemical factors have a significant impact on nutrient cycling (Li et al., 2015). Studies have shown the significant relationship between soil physicochemical factors and ecological stoichiometric ratios. Soil TOC, TN, NiN, and TP were the main driving factors affecting the stoichiometric characteristics of soil C, N, and P. TOC, TN, NiN, and TP were significantly correlated with soil stoichiometric characteristics (Zhang, 2017; Li et al., 2019; Guo et al., 2020). Soil TOC, TN, TP, and NiN can promote the increase in soil C/N, N/P, C/P, and P element, which were likely to be the limiting factors of soil ecological stoichiometric ratio.

## Conclusion

The present study has shown that slope aspect is an important factor affecting soil nutrient and stoichiometric ratio. Altitude has a significant effect on N, P, and C/N ($P < 0.05$); slope aspect has a very significant effect on C, P, C/N, and C/P ($P < 0.01$). The interaction of altitude and aspect has significant effects on P, C/N, and C/P ($P < 0.05$). The soil C/N and N/P in the study area has shown opposite trends with the increase in altitude, and the variations on the altitude gradient were limited by nitrogen. Altitude slightly affects C/N, C/P, and N/P, and slope aspect has significant correlation ($P < 0.05$) or extremely significant correlation ($P < 0.01$) with soil stoichiometric ratio at each altitude. Elucidating changes in soil quality based on studies of soil nutrient element content and stoichiometric ratio alone is insufficient. The interaction between soil nutrient elements must be considered (Tao et al., 2016; Zhu et al., 2013b), and the present study has found a significant relationship between soil nutrient content and stoichiometric ratio. In summary, elevation and aspect explain the limited variation in soil nutrient stoichiometry in the Sejila Mountains. These findings demonstrate the critical role of topographic factors in alpine regions in influencing soil nutrient stoichiometry and advance understanding of soil nutrient interactions in our subalpine forest ecosystems.

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## REFERENCES

[1] Bao, S. D. (2000): Soil and agricultural chemistry analysis. – Chinese Agriculture Press, Beijing.
[2] Batjes, N. (2014): Total carbon and nitrogen in the soils of the world. – Eur J Soil Sci 65: 10-21. https://doi.org/10.1111/ejss.12114_2.
[3] Bui, E. N., Henderson, B. L. (2013): C:N:P stoichiometry in Australian soils with respect to vegetation and environmental factors. – Plant Soil 373: 553-568. https://doi.org/10.1007/s11104-013-1823-9.
[4] Cambardella, C. A., Moorman, T. B., Novak, J. M., Parkin, T. B., Konopka, A. E. (1994): Field-scale variability of soil properties in central Iowa soils. – Soil Sci Soc Am J 58: 1501-1511.https://doi.org/10.2136/sssaj1994.03615995005800050033x.
[5] Chen, X., Yang, Q., Chen, Z., et al. (2017): Distribution of soil easily oxidized organic carbon and its response to soil factors in the tropical coastal forest of Hainan Island, China. – J Central South Univ for Technol 37: 140-145. https://doi.org/10.14067/j.cnki.1673-923x.2017.11.023.
[6] Chen, B., Chen, L. Y. Y., Jiang, L., et al. (2022): C:N:P stoichiometry of plant, litter and soil along an elevational gradient in subtropical forests of China. – Forests 13: 372. https://doi.org/10.3390/f13030372.
[7] Cleveland, C. C., Liptzin, D. (2007): C:N:P stoichiometry in soil: is there a “redfield ratio” for the microbial biomass. – Biogeochemistry 85: 235-252. https://doi.org/10.2307/20456544.
[8] Dorich, R. A., Nelson, D. W. (1983): Direct colorimetric measurement of ammonium in potassium chloride extracts of soils. – Soil Sci Soc Am J 47: 833-836. https://doi.org/10.2136/sssaj1983.03615995004700040042x.
[9] Elser, J., Sterner, R., Gorokhova, E., Fagan, W., Markow, T., Cotner, J., Harrison, J., Hobbie, S., Odell, G., Weider, L. (2000): Biological stoichiometry from genes to ecosystems. – Ecol Lett 3: 540-550. https://doi.org/10.1046/j.1461-0248.2000.00185.x.
[10] Elser, J. J., Acharya, K., Kyle, M., et al. (2010a): Growth rate-stoichiometry couplings in diverse biota. – Ecol Lett 6: 936-943. https://doi.org/10.1046/j.1461-0248.2003.00518.x.
[11] Elser, J., Fagan, W., Kerkhoff, A., Swenson, N., Enquist, B. (2010b): Biological stoichiometry of plant production: metabolism, scaling and ecological response to global change. – New Phytol 186: 593-608.https://doi.org/10.1111/j.1469-8137.2010.03214.x.
[12] Fang, J. Y., Shen, Z. H., Cui, H. T. (2004): The ecological characteristics of mountain and the research content of mountain ecology. – Biodiversity Science 12: 10-19. https://doi.org/10.3321/j.issn:1005-0094.2004.01.003.

[13] Fang, H. J., Cheng, S. L., Yu, G. R., et al. (2014): Experimental nitrogen deposition alters the quantity and quality of soil dissolved organic carbon in an alpine meadow on the Qinghai-Tibetan Plateau. – Appl Soil Ecol 81: 1-11. https://doi.org/10.1016/j.apsoil.2014.04.007.

[14] Garten, C. T., Post, W. M., Hanson, P. J., et al. (1999): Forest soil carbon inventories and dynamics along an elevation gradient in the southern Appalachian Mountains. – Biogeochemistry 45: 115-145. https://doi.org/10.1023/A:1006121511680.

[15] Griffiths, B. S., Spilles, A., Bonkowski, M. (2012): C:N:P stoichiometry and nutrient limitation of the soil microbial biomass in a grazed grassland site under experimental P limitation or excess. – Ecol Proces 1: 1-11. https://doi.org/10.1186/2192-1709-1-6.

[16] Guo, X. L., Guan, T. Z., Liu, J. Y., Miao, C. B., Mao, X. R., Yang, J. J. (2020): Soil stoichiometric characteristics under the canopy of Populus euphratica. – Journal of Gansu Agricultural University 55: 121-127. https://doi.org/10.13432/j.cnki.jgsau.2020.01.016.

[17] Güsewell, S. (2004): N:P ratios in terrestrial plants: variation and functional significance. – New Phytol 164: 243-266. https://doi.org/10.1111/J.1469-8137.2004.01192.X.

[18] Haby, V. A. (1989): Soil no3-n analysis in ca(oh)2 extracts by the chromotropic acid method. – Soil Sci Soc Am J. 53: 308-310. https://doi.org/10.2136/sssaj1989.03615995005300010059x.

[19] Han, W., Fang, J., Guo, D., Zhang, Y. (2005): Leaf nitrogen and phosphorus stoichiometry across 753 terrestrial plant species in China. – New Phytol 16: 377-385. https://doi.org/10.1111/j.1469-8137.2005.01530.x.

[20] He, Z. L., Niu, Y., Jing, W. M. (2015): Effects of different altitudes on soil organic carbon content in Qinghai spruce forest in Haxi forest area of eastern Qilian. – Protection Forest Science and Technology 10: 9-11.

[21] Hou, L. Y., Zhang, Y. Q., Li, Z. C., Shao, G. D., Song, L. G., Sun, Q. W. (2021): Comparison of soil properties, understory vegetation species diversities and soil microbial diversities between Chinese fir plantation and close-to-natural forest. – Forest 12: 632. https://doi.org/10.3390/F12050632.

[22] Jiang, P. K., Xu, Q. F. (2004): Nitrate content of bamboo shoots and its relationship with fertilization. – Journal of Zhejiang Forestry University 21: 10-14. https://doi.org/10.3969/j.issn.2095-0756.2004.01.003.

[23] Jiang, H. M., Li, M. Z., Wang, Q., et.al (2011): Study on soil nutrient condition under different vegetation in Qilian Mountains. – Research of Soil and Water Conservation 18: 166-170. https://doi.org/CNKI:SUN:STBY.0.2011-05-036.

[24] Kong, Q. Y., Xin, X. B., Pan, G. (2009): Study on the nutrient cycle of litter in the ecosystem of the Sharp-pointed and long-bracted fir forest in Sejila Mountains, Tibet. – J Arid Land 23(05): 128-132. https://doi.org/CNKI:SUN:GHZH.0.2009-05-024.

[25] Kumar, A. (2017): Impact of Tibetan ecological disequilibrium on lower riparian regions of Asia. – Tibet Journal 42: 7-16.

[26] Lasota, J., Bońska, E. (2021): C:N:P stoichiometry as an indicator of histosol drainage in lowland and mountain forest ecosystems. – Forest Ecosystems 8(3): 39-39. https://doi.org/10.1186/s40663-021-00319-7.

[27] Li, H. L., Gong, L., Zhu, M. L., Liu, Z. Y., Xie, L. N., Hong, Y. (2015): Soil stoichiometric characteristics of oasis in the northern margin of Tarim Basin. – Acta Pedologica Sinica 52: 1345-1355. https://doi.org/10.11766/trxb201411220585.

[28] Li, S. B., Zhou, L. L., Chen, B. Y., Yang, Q. F., Ding, G. C., Lin, S. Z. (2019): Effects of subtropical tree species conversion on forest soil carbon, nitrogen, and phosphorus stoichiometry. – Journal of Forest and Environment 39: 575-583. https://doi.org/10.13324/j.cnki.jfcf.2019.06.003.

[29] Li, T., Wang, R., Cai, J., Meng, Y., Wang, Z., Feng, X. (2021): Enhanced carbon acquisition and use efficiency alleviate microbial carbon relative to nitrogen limitation under soil acidification. – Ecological Processes 10: 32. https://doi.org/10.1186/S13717-021-00309-1.

[30] Liu, H. M., Cao, L. H., Zeng, J. Q. (2016): Spatial distribution characteristics of soil nitrogen in the gully area of Sejila Mountains in southeastern Tibet. – Acta Oncol 36: 127-133. https://doi.org/10.5846/stxb201407241502.

[31] Liu, J., Li, J., Long, J. (2022): Altitude characteristics of soil ecological stoichiometry and enzyme activity in Southwest Karst Regio. – Journal of Forest and Environment 42: 113-122. https://doi.org/10.13324/j.cnki.jfcf.2022.02.001.

[32] Luo, Y., Li, Q., Wang, C., Zhang, W., Zhang, H., Li, L., Chen, J., Ma, Y. (2015): Spatial variability of soil C/N ratio and its influence factors at a county scale in hilly area of Mid-Sichuan Basin, Southwest China. – Chin. J. Appl. Ecol. 26: 177-185. https://doi.org/10.13287/j.1001-9332.20141124.003.

[33] Ma, H. F., Xie, M. Y., Hu, H., et al. (2020): Effects of forest soil-plant-litter stoichiometry on soil nitrogen fractions at different elevations in the Qinling Mountains. – Chinese Journal of Ecology 39: 749-757. https://doi.org/10.13292/j.1000-4890.202003.013.

[34] Normand, A. E., Smith, A. N., Clark, M. W., Long J. R., Reddy, K. R. (2017): Chemical composition of soil organic matter in a subarctic peatland: influence of shifting vegetation communities. – Soil Sci Soc Am J 81: 41-49. https://doi.org/10.2136/sssaj2016.05.0148.

[35] Qin, H. L., Fu, X. X., Lu, Y., et al. (2019): Ecological stoichiometry of soil C, N and P at different elevations in Maoer Mountain, Guangxi. – Chinese Journal of Applied Ecology 30: 711-717. https://doi.org/10.13287/j.1001-9332.201903.027.

[36] Reich, P. B., Oleksyn, J. (2004): Global patterns of plant leaf N and P in relation to temperature and latitude. – Proc Natl Acad Sci USA 101: 11001-11006. https://doi.org/10.1073/pnas.0403588101.

[37] Sterner, R. W., Elser, J. J., Vitousek, P. (2017): Ecological Stoichiometry: The Biology of Elements from Molecules to the Biosphere. – Princeton University Press, Princeton, NJ.

[38] Tao, Z., Zhang, Y., Zhou, X. (2016): Ecological stoichiometry of surface soil nutrient and its influencing factors in the wild fruit forest in Yili region, Xinjiang, China. – Chin. J. Appl. Ecol 027: 2239-2248. https://doi.org/10.13287/j.1001-9332.201607.002.

[39] Tessier, J. T., Raynal, D. J. (2003): Use of nitrogen to phosphorus ratios in plant tissue as an indicator of nutrient limitation and nitrogen saturation. – J. Appl. Ecol 40: 523-534. https://doi.org/10.1046/j.1365-2664.2003.00820.x.

[40] Tian, H., Chen, G., Chi, Z., et al. (2010): Pattern and variation of C:N:P ratios in China’s soils: a synthesis of observational data. – Biogeochemistry 98: 139-151. https://doi.org/10.1007/s10533-009-9382-0.

[41] Tian, L. M., Zhao, L., Wu, X. D., et al. (2018): Soil moisture and texture primarily control the soil nutrient stoichiometry across the Tibetan grassland. – Sci Total Environ 622-623: 192-202. https://doi.org/10.1016/j.scitotenv.2017.11.331.

[42] Wang, S., Yu, G. (2008): Ecological stoichiometry characteristics of ecosystem carbon, nitrogen and phosphorus elements. – Acta Ecol Sin 28: 3937-3947. https://doi.org/10.3321/j.issn:1000-0933.2008.08.054.

[43] Wang, Y. D., Wei, J. S., Zhou, M., et al. (2020): Soil stoichiometric characteristics in the poplar and birch secondary forests in the southern greater Xing’an Mountains. – Chinese Journal of Soil Science 51: 1056-1064. https://doi.org/10.19336/j.cnki.trtb.2020.05.07.

[44] Wardle, D. A., Walker, L. R., Bardgett, R. D. (2004): Ecosystem properties and forest decline in contrasting long-term chronosequences. – Science 305: 509-513. https://doi.org/10.1126/science.1098778.

[45] Wu, H., Guo, Z., Peng, C. (2003): Land use induced changes of organic carbon storage in soils of China. – Global Chang Biol 9: 305-315. https://doi.org/10.1046/j.1365-2486.2003.00590.x.

[46] Wu, H., Zou, M. R., Wang, S. Q., Wan, H. X. (2019a): Soil ecological stoichiometric characteristics and their response to altitude gradients in the Qinling pine and oak forests. – Ecology and Environmental Sciences 28: 2323-2331. https://doi.org/10.16258/j.cnki.1674-5906.2019.12.003.

[47] Wu, X. L., Zhang, S. R., Pu, Y. L., Xu, X. X., Li, Y. (2019b): Characteristics and influencing factors of soil microbial biomass carbon, nitrogen and phosphorus content in the Western Sichuan Plain. – Chinese Journal of Eco-Agriculture 27: 1607-1616. https://doi.org/10.13930/j.cnki.cjea.190328.

[48] Yang, Y., Luo, Y. (2011): Carbon: nitrogen stoichiometry in forest ecosystems during stand development. – Glob Ecol Biogeogr 20: 354-361. https://doi.org/10.1111/j.1466-8238.2010.00602.x.

[49] Yang, H., Tu, C., Li, Q., Yang, L., Cao, J. (2015): Analysis of C, N and P stoichiometry of secondary forest in different landforms in karst area. – J. South Agr 46: 777-781. https://doi.org/10.3969/j:issn.2095-1191.2015.5.777.

[50] Yuan, Z., Chen, H. Y., Reich, P. B. (2011): Global-scale latitudinal pat-terns of plant fine-root nitrogen and phosphorus. – Nat Commun 2: 344. https://doi.org/10.1038/ncomms1346.

[51] Zechmeister-Boltenstern, S., Keiblinger, K. M., Mooshammer, M., Penuelas, J., Richter, A., Sardans, J., Wanek, W. (2015): The application of ecological stoichiometry to plant-microbial-soil organic matter transformations. – Ecol Monogr 85: 133-155. https://doi.org/10.1890/14-0777.1.

[52] Zeng, Q., Li, X., Dong, Y., Li, Y., Cheng, M., An, S. (2015a): Ecological stoichiometry characteristics and physical-chemical properties of soils at different latitudes on the Loess Plateau. – J. Nat. Resour 30: 870-879. https://doi.org/10.11849/zrzyxb.2015.05.014.

[53] Zeng, Z., Wang, K., Liu, X., Zeng, F., Song, T., Peng, W., Zhang, H., Du, H. (2015b): Stoichiometric characteristics of plants, litter and soils in karst plant communities of Northwest Guangxi. – Chinese J Plant Eco 39: 682-693. https://doi.org/10.17521/cjpe.2015.0065.

[54] Zeng, Q., Rattan, L., Chen, Y., et al. (2017): Soil, leaf and root ecological stoichiometry of Caragana korshinskii on the Loess Plateau of China in relation to plantation age. – PloS One 12: 0168890. https://doi.org/10.1371/journal.pone.0168890.

[55] Zhang, S. (2017): Soil Stoichiometric Characteristics of Spruce Plantations with Different Stand Age Sequences and Their Correlation with Soil Factors. – Gansu Agricultural University, Lanzhou.

[56] Zhang, L., Yang, L., Guo, Y., et al. (2022): Leaf longevity in a Timberline tree species Juniperus saltuaria in the Sergymla Mountains, Southeastern Tibet. – J Resour Ecol 13: 34-40. https://doi.org/10.5814/j.issn.1674-764x.2022.01.004.

[57] Zhao, F., Kang, D., Han, X., Yang, G., Feng, Y., Ren, G. (2015a) Soil stoichiometry and carbon storage in long-term afforestation soil affected by understory vegetation diversity. – Ecol. Eng 74: 415-422. https://doi.org/10.1016/j.ecoleng.2014.11.010.

[58] Zhao, F., Sun, J., Ren, C., Kang, D., Deng, J., Han, X., Yang, G., Feng, Y., Ren, G. (2015b) Land use change influences soil C, N, and P stoichiometry under ‘Grain-to-Green Program’ in China. – Sci. Rep 5: 10195. https://doi.org/10.1038/srep10195.

[59] Zhong, G. H., Xin, X. B. (2004): Study on the chemical properties of the litter layer of dark coniferous forest in Sejila Mountains, Tibet. – Chinese Journal of Applied Ecology 15: 167-169. https://doi.org/CNKI:SUN:YYSB.0.2004-01-037.

[60] Zhu, L. Y., Pan, J. J., Zhang, W. (2013a): Study on soil organic carbon pools and turnover characteristics along an elevation gradient in Qilian Mountain. – Environmental Science 34: 668-675. https://doi.org/CNKI:SUN:HJKZ.0.2013-02-043.

[61] Zhu, Q., Xing, X., Zhang, H., An, S. (2013b): Soil ecological stoichiometry under different vegetation area on loess hilly-gully region. – Acta Ecol. Sin 33: 4674-4682. https://doi.org/10.5846/stxb201212101772.

[62] Zhu, J., He, W., Yao, J., Yu, Q., Jandug, C. M. B. (2020): Spectral reflectance characteristics and chlorophyll content estimation model of Quercus aquifolioides leaves at different altitudes in Sejila Mountain. – Applied Sciences 10: 3636. https://doi.org/10.3390/app10103636.

# APPENDIX

***Table A1.** Altitudinal distribution characteristics of stoichiometric ratios in north and south slopes*

| Aspect | Altitude | C/N |  | C/P |  | N/P |  |
|---|---|---|---|---|---|---|---|
|  |  | Mean ± SD | CV/% | Mean ± SD | CV/% | Mean ± SD | CV/% |
| North slope | 3800 | 20.87 ± 2.29 | 10.98 | 109.30 ± 3.68 | 3.37 | 5.28 ± 0.61 | 11.56 |
|  | 3900 | 15.03 ± 1.13 | 7.52 | 72.07 ± 5.83 | 8.09 | 4.83 ± 0.72 | 14.97 |
|  | 4000 | 13.73 ± 0.51 | 3.68 | 65.24 ± 3.27 | 5.01 | 4.75 ± 0.28 | 5.86 |
|  | 4100 | 13.27 ± 3.26 | 24.55 | 66.64 ± 13.44 | 20.16 | 5.28 ± 1.81 | 34.23 |
|  | 4200 | 13.17 ± 3.26 | 24.55 | 66.64 ± 13.44 | 20.16 | 5.28 ± 1.81 | 34.23 |
|  | 4300 | 13.82 ± 1.32 | 9.53 | 89.31 ± 33.41 | 30.07 | 6.65 ± 3.17 | 47.65 |
| South slope | 3800 | 22.55 ± 3.91 | 17.34 | 76.00 ± 32.59 | 42.88 | 3.57 ± 2.01 | 56.50 |
|  | 3900 | 32.02 ± 11.03 | 34.45 | 171.32 ± 74.17 | 43.29 | 5.26 ± 0.82 | 15.63 |
|  | 4000 | 16.66 ± 0.25 | 1.51 | 114.99 ± 25.34 | 22.04 | 6.91 ± 1.54 | 22.27 |
|  | 4100 | 19.75 ± 2.38 | 12.03 | 113.08 ± 10.29 | 9.10 | 5.76 ± 0.65 | 11.30 |
|  | 4200 | 18.46 ± 2.41 | 13.05 | 132.25 ± 41.92 | 31.7 | 7.32 ± 2.63 | 35.93 |
|  | 4300 | 17.83 ± 2.05 | 11.48 | 131.93 ± 7.57 | 5.74 | 7.49 ± 1.24 | 16.55 |

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