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Original Research

Stoichiometry Characteristics of C, N, and P of Soil Profiles along an Altitude Gradient in Luofu Mountain, Guangdong

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Abstract

The vertical distribution and stoichiometry characteristics of soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP) of soil profiles along an altitude gradient were investigated in Luofu Mountain, Guangdong. A total of ten sites at different altitude gradients in Luofu Mountain were selected and soil genetic horizon samples were collected. Soil physic-chemical properties, such as bulk density, soil particle-size composition, pH, SOC, TN, TP, total iron oxides (Fe_t), free iron oxides (Fe_d), amorphous iron oxides(Fe_o), CEC, etc, were determined to analyze the correlation of SOC, TN, TP, C:N ratio, C:P ratio, N:P ratio with altitude gradients, physic-chemical properties. Our findings suggest that with the increase of soil depth, SOC, TN, TP, C:N ratio, C:P, and N:P in Luofu Mountain decreased, While with the increase of altitude, SOC, TN, TP, C:P , N:P increased, C:N ratio increased, and SOC, TN, TP highly significantly or significantly correlated with altitude. Pearson correlation analysis showed that SOC, TN, TP had highly significant positive correlations with silt, Fe_o, Fe_o:Fe_d, CEC. SOC and TN were highly significantly or significantly negatively correlated with clay, bulk density, Fe_t, Fe_d. TP had highly significant negative correlation with bulk density; C:N ratio, C:P ratio and N:P ratio showed highly significant positive correlation with CEC, while were highly significantly negatively correlated with bulk density, Fe_t, Fe_d. Redundancy analysis (RDA) showed that bulk density, clay, CEC, Fe_t, Fe_o and sand had highly significant effect on the stoichiometric characteristics of SOC, TN, TP, while altitude, pH, Fe_d, Fe_d:Fe_t ratio and Fe_o:Fe_d ratio had no significant effect. It was found that bulk density, clay, CEC, Fe_t and Fe_o are main soil physic-chemical factors that regulate the stoichiometric characteristics of SOC, TN, TP at different altitudes in the study area.

Keywords: stoichiometry characteristics, C, N and P, soil profile, altitude, Luofu Mountain

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Introduction

Soil is an important component of terrestrial ecosystems, providing the mineral nutrient elements for plant growth, especially carbon (C), nitrogen (N), and phosphorus (P), which are the main components of soil nutrients, play a crucial role in ensuring ecosystem health and its nutrient cycling [1-3]. Ecological chemometrics, as a science to study the energy balance and multiple chemical element balance of biological systems, has become a new method to study the change pattern and coupling relationship of nutrient elements such as C, N and P in the ecosystem [4-8]. The study of the ecological stoichiometry of C, N and P in soil is important for understanding the coupled ecosystem nutrient cycle and achieving sustainable management of ecosystem service functions [5, 9-11].

So far, a large number of studies on the ecological stoichiometry of C, N and P in soil have been reported, and it was found that they are strongly influenced by climate, topography, vegetation cover, parent material:rock, utilization, soil microorganisms and other factors [9, 12-14]. Li et al. found that soil organic carbon (SOC) content and total nitrogen (TN) content increased and then decreased with increasing altitude, while total phosphorus (TP) content showed less spatial variability; C:N and C:P decreased with increasing altitude in broadleaf forest and increased in coniferous forest, and N:P increased and then decreased with increasing altitude, by studying the ecological chemometric characteristics of carbon, nitrogen and phosphorus in Taibai [5]. The soil C, N and P stoichiometry characteristics in Tianma National Nature Reserve showing that with increasing altitude, soil SOC content and TN content in different soil layers showed a decrease followed by an increase, while soil TP content shows an increase followed by a decrease; with increasing altitude gradient, soil C:N in different soil layers first increased and then decreased, and C:P and N:P first decreased and then increased [15]. In Mao'er Mountain, with increasing altitude, soil SOC content, TN content, C:P and N:P all showed increasing [16]. Zhang et al. investigated the stoichiometric characteristics of soil C, N and P at different altitudes in Xiaojiang Watershed, showing that soil SOC content, TN content, C:P, N:P, and TP content all showed increasing with increasing altitude gradient, while TP content decreased, and the sensitivity of SOC, TN and TP to altitude decreased in order [17].

Although researchers have studied the distribution characteristics of SOC, soil occurrence characteristics and classification in Luofu Mountain [18, 19], there is still no relevant study on soil C, N, P stoichiometry characteristics. In this study, we analyzed the vertical distribution patterns of soil C, N and P contents and stoichiometric characteristics at different altitudes, and dissected the influencing factors of soil C, N and P contents and stoichiometric characteristics in Luofu Mountain. The results provide scientific basis for the utilization and management of soil resources and conservation of forest ecosystem in Luofu Mountain.

Materials and Methods

Study Site Description

This study was conducted at the Luofu Mountain (113°51′~114°03′E, 23°13′~23°20′N), Huizhou City, Guangdong Province, China. The highest peak Feiyun mountain has a maximum altitude of 1856 m. The total area is 9827.7 hm^2, this region has a southern subtropical monsoon climate, with a mean annual precipitation of 1934.3 mm and a mean annual temperature of 22.3ºC. Luofu Mountain is rich in plant species, mainly tropical and subtropical broad-leaved evergreen plants [19].

Experiment Design and Soil Sampling

In this study, 10 representative soil samples were selected from different altitudes of Luofu Mountain with granite development (vertical height interval of sample sites is 100 m). Natural locations free of disturbance were selected, profile toward the direction of sunlight. The excavation profiles, according to the elevation from high to low, were marked as LF01~LF10, and the excavation depths of the profiles were 83 cm, 108 cm, 75 cm, 82 cm, 80 cm, 130 cm, 60 cm, 115 cm, 130 cm, 140 cm in order. A total of 42 samples were collected according to the soil genetic horizon, and the number of samples collected was 4, 4, 3, 4, 4, 5, 4, 4, 5 and 5 in order, and each profile was described and documented (Table 1). In July 2021, the collected samples were taken to the laboratory to remove impurities such as branches and leaves, air-dried indoors for 7 d, fully ground using a mortar, and passed through 10 mesh, 60 mesh and 100 mesh nylon sieves, respectively. and the samples were encapsulated in PE plastic bags to be marked and sealed for storage and testing. Then, the samples were placed in a sealed container for measurement.

Measurement of soil physical and chemical properties: Total P (TP) was measured colorimetrically after the digestion with H_2SO_4 and $HClO_4$. Soil pH value, SOC, TN, cation exchange capacity (CEC), total iron content (Fe_t), DCB-extractable iron content (Fe_d), oxalate extractable iron (Fe_o) were measured according to Dong et al. [19].

Statistical Analysis

The data were statistically analyzed using SPSS 20.0 (SPSS Inc., Chicago, IL, USA) and Origin 2016 (OriginLab, Northampton, USA). Redundancy analysis was conducted using Canoco 5.0. The soil C, N and P stoichiometric ratios in this study were all elemental mass ratios.

Table 1. Basic information of soil sampling sites.

Profile No.	Altitude	Depth of profile	Number of samples	Slope (°)	Coordinate (°)	Soil type	Vegetation type
LF01	1210	83	4	<5	114.01943E, 23.28193N	Humic Ali-Perudic Cambosols	Mountain Meadows
LF02	1140	108	4	5~10	114.02588E, 23.27869N	Typic Alliti-Perudi Ferrosols	Bushes and grasses
LF03	1001	75	3	25~35	114.02270E, 23.27341N	Typic Alliti-Perudi Ferrosols	Bushes and grasses
LF04	900	82	4	5~10	114.02274E, 23.27112N	Typic Alliti-Perudi Ferrosols	Bushes and grasses
LF05	800	80	4	10~15	114.02498E, 23.26963N	Typic Alliti-Perudi Ferrosols	Subtropical broadleaf evergreen forests
LF06	700	130	5	5~10	114.02530E, 23.26717N	Typic Hi-weatheri-Udic Ferrosols	Subtropical broadleaf evergreen forests
LF07	600	60	4	25~35	114.02776E, 23.26689N	Argic Hi-weatheri-Udic Ferrosols	Subtropical broadleaf evergreen forests
LF08	500	115	4	10~15	114.03452E, 23.25799N	Typic Alliti-Udic Ferrosols	Subtropical broadleaf evergreen forests
LF09	370	130	5	5~10	114.04676E, 23.26937N	Typic Alliti-Udic Ferrosols	Subtropical broadleaf evergreen forests
LF10	280	140	5	5~10	114.04938E, 23.26781N	Typic Hi-weatherii-Udic Ferrosols	Subtropical Seasonal Rainforests

Results

Distribution Characteristics of Soil C, N and P Content at Different Altitudes Gradient

The SOC, TN and TP contents of soil at different altitudes gradient in Luofu Mountain range from 1.22 $g\cdot kg^{-1}$~60.53 $g\cdot kg^{-1}$, 0.10 $g\cdot kg^{-1}$~4.25 $g\cdot kg^{-1}$ and 0.07 $g\cdot kg^{-1}$~0.52 $g\cdot kg^{-1}$, respectively (Fig. 1). The trends of the SOC, TN and TP contents within the soil are the same, showing a distribution of "high at the top layer and low at the bottom layer", the SOC content, TN content and TP content gradually decrease with the depth of the soil layer, however, the increase of TP content was less obvious compared with SOC and TN content (Fig. 1).

Soil SOC, TN and TP contents increased with increasing altitude, and there was a significant positive correlation between altitude and soil SOC and TP contents (r_C = 0.3625, P<0.05; r_P = 0.3726, P<0.05), while a highly significant positive correlation was found between altitude and TN content (r_N = 0.3981, P<0.01), indicating altitude has a significant effect on soil SOC, TN and TP content (Fig. 2).

Stoichiometry Characteristics of C, N and P in Soil Profiles at Different Altitudes

The profile distribution patterns of C, N, P stoichiometric ratios of soil profiles at different altitude in Luofu Mountain are shown in Fig. 3. The ranges of C:N, C:P, and N:P ratios were 9.49~18.58, 5.05~249.53, and 0.44~14.01, respectively. With the increase of soil depth, the ratios of C:N, C:P, and N:P were all decrease, which was consistent with the distribution of C, N and P contents within the profile. The degree of soil C:N variation at different altitude was not significant relative to C:P and N:P (Fig. 3). Relationships between altitude gradient and stoichiometric characteristics of soil C, N and P were shown in Fig.4, and the results demonstrate that C:N decreased with increasing altitude, while C:P and N:P increased, but none of them showed significant differences. ($r_{C:N}$ = -0.0045, P>0.05; $r_{C:P}$ = 0.1549, P>0.05; $r_{N:P}$ = 0.1836, P>0.05).

Relationship between Soil C, N and P Contents and Stoichiometric Characteristics and Soil Physicochemical Properties

The Pearson correlation analysis of soil C, N, P content and stoichiometric characteristics with soil physicochemical properties is shown in Table 3, which indicates SOC content, TN content, C:N, C:P and N:P are highly significant positive correlation with each other; TP content is positive correlation with SOC content and TN content. The relationships between soil C, N and P contents and stoichiometric characteristics and soil physicochemical properties showed that SOC content, TN content and TP content

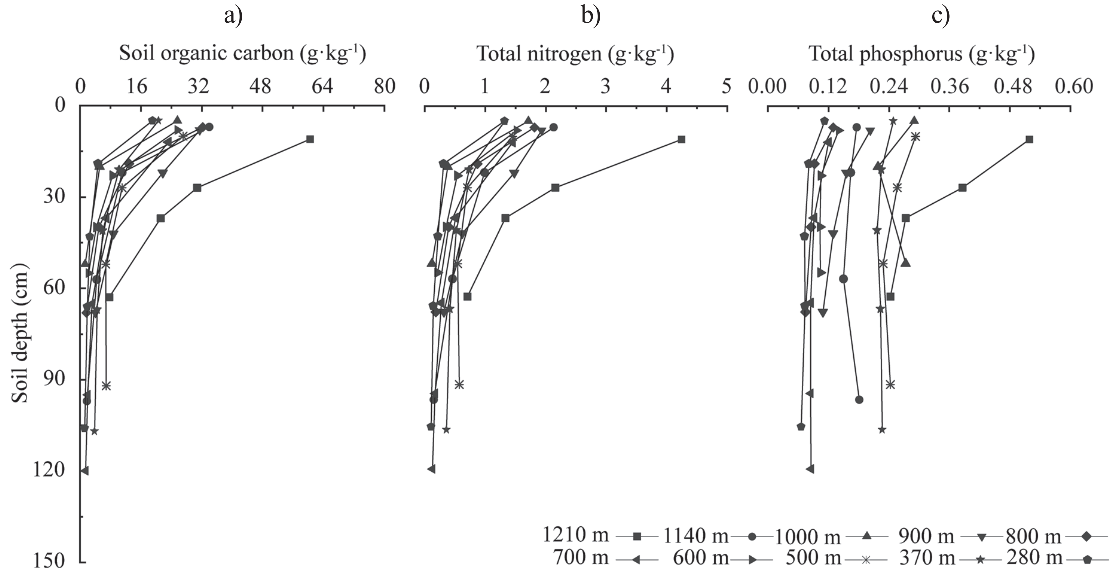

Fig. 1. The distribution of contents of soil C a), N b), P c) in soil profile at different altitudes.

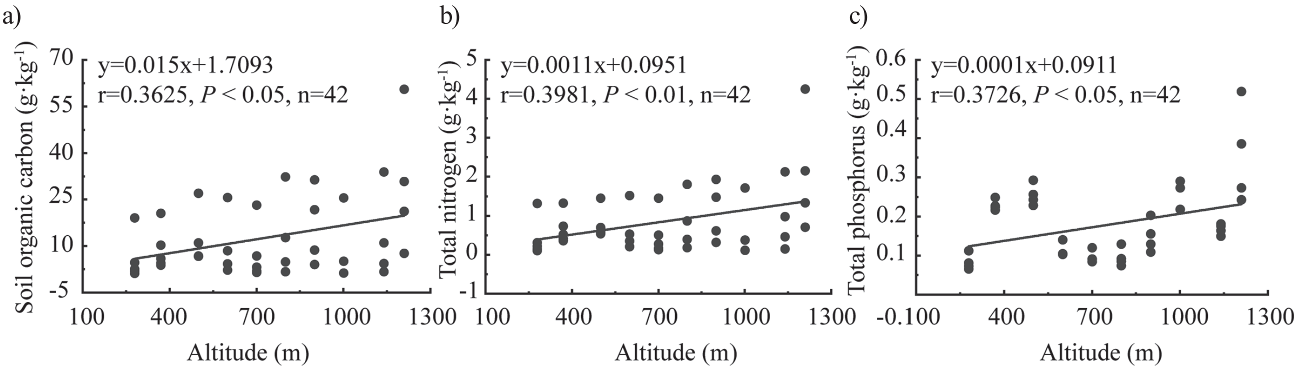

Fig. 2. Relationships between altitude gradient and contents of soil C a), N b), P c). *$P<0.05$ indicates a significant difference in the relationship between altitude and soil C and P content, and **$P<0.01$ indicates a highly significant difference in the relationship between altitude and soil N content.

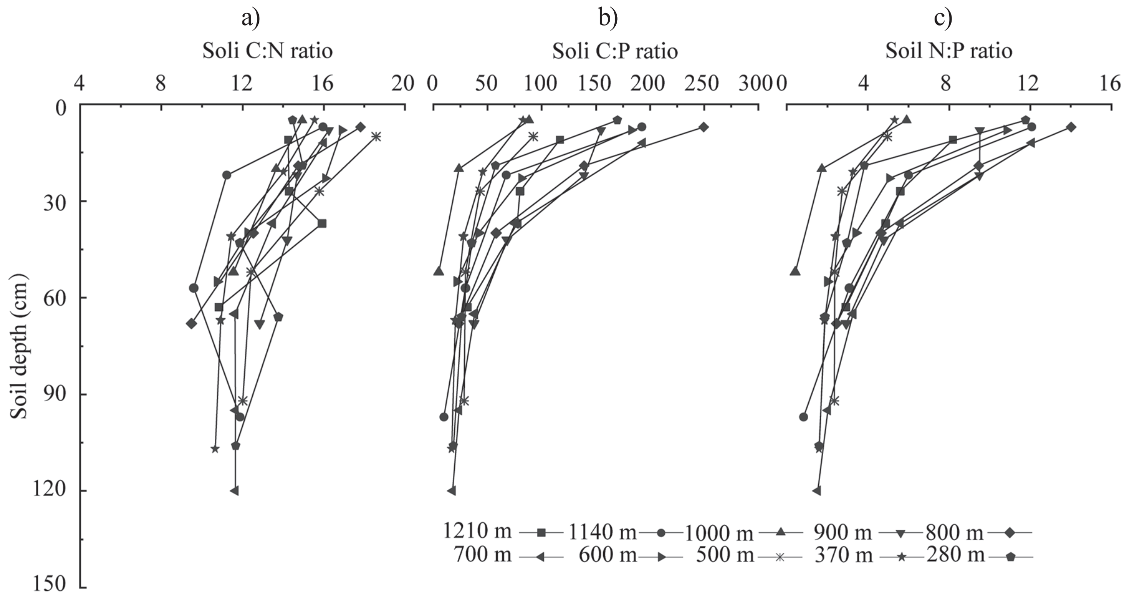

Fig. 3. The distribution of stoichiometric characteristics of C a), N b), P c) in soil profile at different altitudes.

Table 2 Basic properties of the studied soils

Profile No.	Number of samples	Bulk density ($g \cdot cm^{-3}$)	Soil particle composition (%)			pH	Fe_t ($g \cdot kg^{-1}$)	Fe_d ($g \cdot kg^{-1}$)	Fe_o ($g \cdot kg^{-1}$)	CEC (cmol (+) kg^{-1})
			Sand	Silt	Clay					
LF01	4	0.93~1.38	39.97~66.48	20.97~43.47	12.44~19.12	3.69~4.16	21.54~26.74	13.51~15.31	8.21~9.93	7.24~25.68
LF02	4	1.03~1.6	48.76~55.55	22.77~25.52	21.44~27.32	3.95~4.25	22.81~29.12	12.33~19.37	1.41~6.45	4.92~13.75
LF03	3	1.1~1.61	53.77~61.99	14.37~20.95	22.72~25.28	4.14~4.46	27.81~34.32	14.98~17.42	0.51~3.30	5.33~10.76
LF04	4	0.93~1.6	52.09~62.07	17.98~22.23	19.96~27.12	4.28~4.79	21.26~25.26	10.73~14.39	0.65~2.15	4.89~12.09
LF05	4	1.08~1.52	53.62~61.61	16.83~21.38	21.56~25.76	4.01~4.52	19.28~24.68	9.89~11.86	0.41~2.00	4.85~11.05
LF06	5	1.17~1.57	45.69~54.02	17.14~21.79	25.48~32.92	4.09~4.83	24.91~30.93	14.76~19.21	0.34~1.63	4.43~10.22
LF07	4	1.35~1.61	44.27~58.49	12.31~21.75	27.64~38.28	4.12~4.46	28.05~39.23	16.27~23.52	0.60~1.89	5.64~9.50
LF08	4	1.12~1.42	45.4~47.96	21.44~27.24	27.36~32.60	4.14~4.78	33.51~36.46	12.69~14.27	1.89~2.75	6.98~14.22
LF09	5	1.24~1.49	35.86~46.92	17.84~21.22	35.24~43.96	4.10~4.40	34.46~46.62	19.45~27.56	0.75~1.72	6.88~9.70
LF10	5	1.09~1.58	41.98~55.44	18.13~23.3	23.52~34.72	4.20~4.69	24.65~33.91	13.06~18.81	0.30~1.61	4.45~7.73

were highly significantly and positively correlated with silt, Fe_o, Fe_o:Fe_d and CEC; SOC content and TN content were significantly negatively correlated with clay, bulk density, Fe_t and Fe_d; TP content and bulk density showed a highly significant negative correlation level; C:N, C:P and N:P were all negatively correlated with each other. C:N, C:P and N:P were all highly significantly and positively correlated with CEC, and all were highly significantly and negatively correlated with bulk density, Fe_t and Fe_d.

Two-dimensional sequence diagram of Redundancy analysis (RDA) was performed between soil physicochemical properties-environmental factors and C, N, P cotent and stoichiometric characteristics of C, N and P. The results indicate (Fig. 5) that the RDA I and II explained 84.46% and 6.23% of the variation in soil C, N, and P stoichiometric characteristics, respectively, with a cumulative explanation of 90.71%. Table 4 shows that the order of explanation rate of soil physicochemical properties-environmental factors is: bulk density>Fe_t >clay>CEC>Fe_o>sand>altitude>Fe_d>pH>Fe_o:Fe_d > Fe_d:Fe_t, where the factors that significantly affect the stoichiometric characteristics of soil C, N, and P include bulk, Fe_t, clay, and CEC ($P<0.01$), and Fe_o and sand ($P<0.05$), however, altitude, Fe_d, pH, Fe_o:Fe_d, and Fe_d:Fe_t had insignificant effects on soil C, N, and P stoichiometric characteristics ($P>0.05$).

Disscussion

Characteristics of Soil C, N and P Content

Soil C, N, P and other mineral elements are the main nutrients of plant nutrition in forest ecosystems, which are characterized by significant spatial heterogeneity [5, 20]. The distribution characteristics of C, N and P contents in the soil profile are strongly influenced by soil depth [21, 22], in this study, the distribution of SOC, TN and TP contents in the profile at different altitude showed decreasing with soil depth, and the SOC and TN contents showed obvious surface convergence phenomenon, while the TP contents did not differ significantly among the soil depth (Fig. 1), in agreement with the results of Qin et al. and Deng et al. on the soil C, N and P in Mao'er Mountain [16, 23]. Since SOC and N in forest soils are mainly derived from vegetation apoplastic nutrient return, apoplastic decomposition first accumulates in the surface layer and then migrates to the lower layer by leaching, which is influenced by apoplastic decomposition and soil microorganisms [11, 15]; while the soil TP content is mainly derived from the parent material, therefore, TP content did not vary significantly within the profiles. In conclusion, our result suggests that the sources of C, N and P play a decisive influence on their content distribution within the soil profile.

Soil SOC, TN, and TP contents showed increasing with altitude, and all showed significant positive

Table 3. Correlations of contents and stoichiometric characteristics of soil C, N, P with soil physical and chemical properties.

Properties	SOC	TN	TP	C:N	C:P	N:P
SOC	1.000	0.990**	0.617**	0.663**	0.744**	0.737**
TN		1.000	0.660**	0.573**	0.687**	0.695**
TP			1.000	0.202	0.034	0.021
C:N				1.000	0.748**	0.679**
C:P					1.000	0.990**
Sand	-0.081	-0.105	-0.195	-0.045	0.083	0.078
Silt	0.646**	0.690**	0.644**	0.249	0.199	0.215
Clay	-0.375*	-0.382*	-0.256	-0.131	-0.229	-0.234
Bulk density	-0.895**	-0.868**	-0.452**	-0.712**	-0.790**	-0.781**
pH	-0.344*	-0.401**	-0.373*	0.028	-0.156	-0.201
Fe_t	-0.388*	-0.368*	0.121	-0.350*	-0.552**	-0.577**
Fe_d	-0.322*	-0.287	0.006	-0.404**	-0.426**	-0.423**
Fe_o	0.572**	0.629**	0.655**	0.13	0.195	0.233
Fe_d:Fe_t	0.068	0.103	-0.15	-0.153	0.122	0.171
Fe_o:Fe_d	0.609**	0.655**	0.646**	0.206	0.259	0.288
CEC	0.929**	0.944**	0.791**	0.491**	0.500**	0.497**

Note: The Pearson correlation analysis method was used. "*" means significant correlation at 0.05 level; "**" means significant correlation at 0.01 level.

correlations with altitude (Fig. 2). This is mainly due to the fact that the temperature gradually decreases and relative humidity gradually increases with increasing altitude in mountainous areas, and this hydrothermal condition leads to weaker soil microbial activity, decomposition rate of plant and animal residues and mineralization rate of soil organic C and N slowed down, thus, facilitates the accumulation of SOC and TN content [16]; slower decomposition rate of plant and animal residues and mineralization rate of soil organic C and N, which facilitates the accumulation of SOC and TN contents; soil P [16-17], although mainly derived from rock weathering and poorly migrated, is also affected by temperature and rainfall [26], our findings differ from those of Li et al., Qin et al., and Zhang et al. [5, 15, 16]. In summary, the patterns of soil SOC, TN and TP contents with altitude under different biotic or abiotic factor conditions showed diverse changes.

Soil C, N, P Stoichiometry Characteristics

The modulation by factors such as topography, regional hydrothermal conditions, leads to a wide variation in the content of nutrients such as C, N, and P within the soil profile at different altitude [5, 17, 27], in agreement with our study (Fig. 1). In this study, C:N,

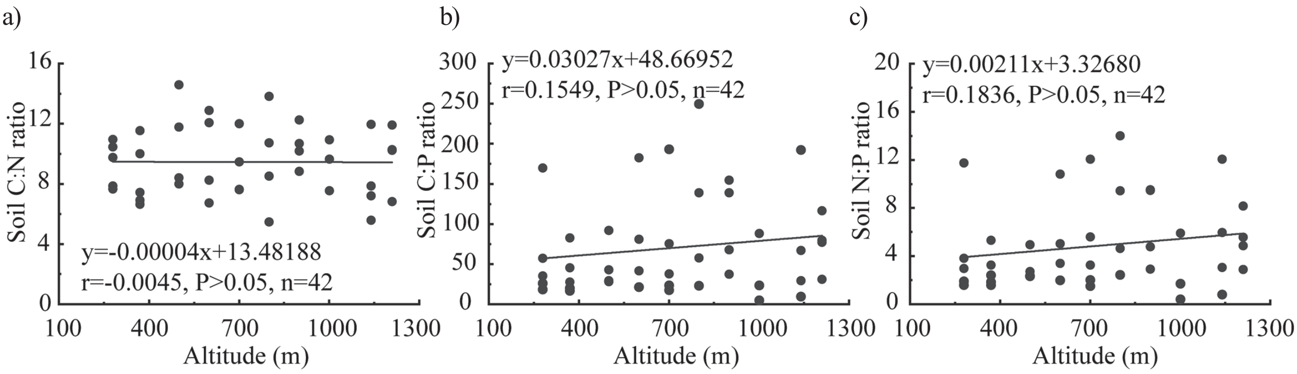

Fig. 4. Relationships between altitude gradient and stoichiometric characteristics of soil C a), N b) and P c). P>0.05 indicates no significant difference in the relationship between altitude and soil carbon, nitrogen and phosphorus stoichiometric characteristics.

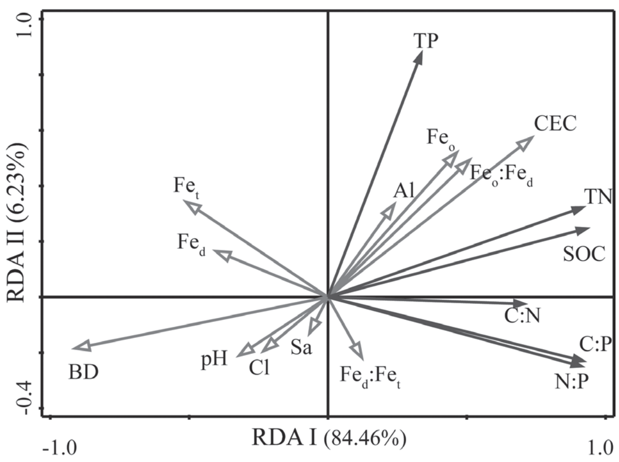

Fig. 5 Two-dimensional sequence diagram of RDA analysis between soil physical and chemical properties-environmental factors and C, N, P and their stoichiometric characteristics. SOC: Soil organic cabon; TN: Total nitrogen; TP: Total phosphorus; C:N: Ratio of soil organic cabon to total nitrogen; C:P: Ratio of soil organic cabon to total phosphorus; N:P: Ratio of total nitrogen to total phosphorus; BD: Bulk density; Al: Altitude; Sa: Sand; Si: Silt; Cl: Clay; Fe_t: Total Fe; Fe_d: Free Fe; Fe_o: Amorphous Fe; Fe_d:Fe_t: Ratio of Fe_d to Fe_t; Fe_d:Fe_t: Ratio of Fe_o to Fe_d.

C:P, and N:P all tended to decrease with increasing soil depth, but the degree of variability of C:N within the soil was small relative to C:P and N:P (Fig. 3), which is consistent with the results of most studies [8, 13, 16]. Due to the fact that soil SOC, TN, and TP contents gradually decrease with increasing soil depth, among which, TN has the effect of atmospheric nitrogen deposition and organic matter mineralization as supplementary sources to slow down the rate of decrease [28]. In addition, TP content, although decreased, did not differ significantly between soil layers [23]. C:N decreased with increasing altitude, which is consistent with the findings of Gao et al. on soil at different altitudes in the Qilian Mountains [29]. And the C:P and N:P at different altitudes were similar to the results of Wang et al. [30], which showed increasing with altitude, but none of them showed significant difference (Fig. 4). Overall, the variation patterns of soil C/N, C/P, and N/P in different study areas were less influenced by biotic and abiotic factors.

Table 4. Explanation rate and significance test of soil physical and chemical properties-environmental factors.

Properties	Explanation rate (%)	F	P
Bulk density	70.20	94.3	0.002
Fe_t	4.30	6.70	0.006
Clay	7.00	14.4	0.002
CEC	5.30	14.8	0.002
Fe_o	1.30	3.90	0.042
Sand	1.20	3.80	0.0424
Altitude	0.70	2.50	0.086
Fe_d	0.70	2.60	0.098
pH	0.20	0.80	0.444
Fe_o/Fe_d	0.10	0.50	0.514
Fe_d/Fe_t	<0.10	0.20	0.860

Factors Influencing the Soil C, N, P Soichiometric Characteristics

Soil C, N and P stoichiometric characteristics are regulated by soil C, N and P contents, and also by soil physicochemical properties [13-16]. In our research, the correlations among SOC content, TN content, TP content, C:N, C:P, and N:P in Luofu Mountain indicating that the changes in C:N, C:P, and N:P were mainly influenced by SOC content and TN content, while they were less influenced by TP content (Table 2), which may be related to the fact that the source of TP in forest soils is mainly parent material.

The combined Pearson and RDA analyses showed that bulk density, silt, clay, Fe_t, CEC and Fe_o were the main soil physicochemical factors affecting the stoichiometric characteristics of soil C, N and P in the Luofu Mountain (Table 3 and 4). The bulk density and CEC show highly significant correlation with soil SOC, TN, TP contents and C:N, C:P and N:P (Table 3), and was the most significant influencing factor for soil C, N, P stoichiometric characteristics, providing 75.5% of the explanation rate (Table 4). It has been shown that the bulk density can influence the accumulation of C, N and P in the soil; when the bulk density is low, it is beneficial to the growth of plant roots and the mineralization and decomposition of residues, which in turn affects the migration and accumulation of C, N and P in the soil [25, 31]. Soil Fe_t was significantly or highly significantly negatively correlated with SOC content, TN content, C:N, C:P and N:P, Fe_o was highly significantly positively correlated with SOC, TN and TP content, and clay was significantly negatively correlated with SOC and TN, also, clay was negatively correlated with TP, although it did not show significant difference with TP (Table 3). Consistent with the studies of other scholars, Fe_o, and CEC increased and clay and Fe_t decreased with increasing altitude [18, 32]. In conclusion, our study demonstrated that indicators such as bulk density, clay, Fe_t, CEC and Fe_o in the study area have a significant influence on the patterns of C, N and P content and stoichiometric characteristics.

Conclusions

With the increase of altitude, soil SOC, TN and TP contents increased, and correlation analysis showed that there were significantly positive relationships ($P<0.01$)

between altitude and SOC, TN and TP contents; ratios of C:N showed decreasing, and C:P and N:P showed increasing, but none of them showed significant levels. The soil SOC, TN and TP contents and C:N, C:P and N:P ratios decreased with the increase of soil depth. Bulk density, clay, Fe_t, CEC and Fe_o were the main soil physicochemical factors affecting the stoichiometric characteristics of soil C, N, and P in our study.

Acknowledgments

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Conflict of Interest

The authors declare no conflicts of interest.

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