Pol. J. Environ. Stud. Vol. 31, No. 3 (2022), 2905-2914
DOI: *10.15244/pjoes/144101* ONLINE PUBLICATION DATE: 2022-02-28

Original Research

Variations in Ecological Stoichiometry Characteristics of C, N and P in Soils Beneath an *Abies fanjingshanensis* Forest

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Received: 2 July 2021
Accepted: 20 November 2021

Abstract

Spatiotemporal changes in the ecological stoichiometry characteristics of soils beneath an *Abies fanjingshanensis* forest and their driving factors were investigated to provide essential data for the conservation of this species. The soil physical and chemical indices beneath an *A. fanjingshanensis* forest in different years were studied. Specifically, the ecological stoichiometric characteristics of soils in 1980, 2000, and 2020 were compared through field sampling and laboratory analysis. The organic matter content in different years was 2020>2000>1980. In general, soil pH, soil organic matter, total nitrogen and available phosphorus displayed an increasing trend, while total phosphorus, total potassium and available potassium contents did not change significantly, and the alkali hydrolysable nitrogen content showed a gradual increasing trend. Specifically, C/P and N/P ratios in the 0-20 cm soil layer maintained an upwards trend, but the variation of C/N in soils was insignificant. Over time, the content of soil sand increased, whereas the clay contents decreased; moreover, the content of cations was much lower than the average value in Chinesee soil. Among the variety of influencing factors, soil silt was significantly negatively associated with pH. Sand was significantly positively associated with available P, while clay particles were significantly negatively associated with available P. In summary, P in soil is the principal factor restricting the growth of *A. fanjingshanensis*.

Keywords: Mount Fanjing, Abies, carbon, nitrogen, phosphorus

Introduction

Carbon (C), nitrogen (N), and phosphorus (P) are basic elements constituting a plant body and are of great significance to the growth and function of plants [1, 2]. C, N, and P in the soil are critical elements that can restrict plant growth; they are also quantitative indices for measuring the degree of soil fertility and important indicators of the ecological functions of soil [3]. It is worth noting that the cycle characteristics of C, N, and P in forest ecosystems are remarkably variable in different regions under the influences of different biological characteristics, forest management methods and regional climates [4, 5]. Hence, studying the stoichiometric characteristics of forest ecosystems

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indicate their function in nutrient cycling and restriction during forestation [6-8]. Scholars researching C, N and P cycles have conducted numerous studies on soil nutrients using stoichiometry. More precisely, some scholars have studied the impacts of N and P inputs of varied ratios and levels on soil pH and stoichiometric characteristics in the temperate grasslands of Inner Mongolia [9]. Other scholars have studied the characteristics of ecological stoichiometry, the distribution of nutrient elements and their variations in the herb community to clarify the response mechanism and adaptability of the herb community to environmental variations [10-13]. Ashraf et al. [14] discussed the responses of soil organic carbon (SOC) and nitrogen mineralization to variations in microbial biomass and SOC as well as N and P stoichiometric characteristics caused by long-term fertilization. Li et al. [15] studied ways of measuring the stoichiometry of C, N and P in plants and soil with urine, faeces, and their mixtures as well as their interactions. Scholars worldwide have investigated soil in different environments using chemometric methods. However, few studies can be found on the stoichiometric characteristics of soils under *Abies fanjingshanensis*, which is a rare and endemic species.

Mount Fanjing, located in Guizhou, China, has suitable topography and mountain climatic conditions for the growth of *Abies* species. *A. fanjingshanensis* is an endemic plant to Mount Fanjing and is also a rare species in the genus *Abies* since it is found only in some areas of Mount Fanjing. *A. fanjingshanensis* remains in localized areas of Mount Fanjing but is scarce and extremely narrowly distributed. It should be prevented from going extinct due to its low maturation rate and inadequate natural regeneration. The protection of *Abies* has been highly valued by relevant departments. Most of the canopies of *A. fanjingshanensis* cannot be closed due to the invasion of other dominant forest plants. *A. fanjingshanensis* is dying out with fewer and fewer new trees, which has been ongoing since its discovery in 1980. Therefore, site research and protection of *A. fanjingshanensis* should be conducted without delay. Hence, this study focuses on soils beneath *A. fanjingshanensis* forests in 1980, 2000, and 2020 and examines the spatiotemporal evolution of the stoichiometric characteristics of these soils. Then, the availability of nutrients in the soil of *A. fanjingshanensis* as well as the circulation, balance mechanism and mutual restriction of C, N, and P in the soil were determined using ecological stoichiometric characteristics of C, N, and P. This paper can provide a theoretical foundation for the protection of *A. fanjingshanensis* and other rare plants.

Overview of the Study Area

The study area, is the main peak of the Wuling Mountains, is located at Mount Fanjing (27°49′50″N-28°1′30″N, 108°45′55″ E-108°48′30″ E), which borders Yinjiang, Jiangkou, and Songtao counties, in Tongren, Guizhou, China. It is part of the subtropical humid monsoon climate zone under the control of the Southeast Asian Pacific monsoon. Hence, it is remarkably affected by the southeast ocean monsoon in summer and less affected by cold temperatures in winter. The annual average temperature of Mount Fanjing ranges from 13.1ºC to 14.7ºC, and the average temperatures in the hottest month and coldest month are 25.3ºC and 2ºC, respectively. Note that the temperature decreases as the terrain increases. The annual frost-free period, annual sunshine hours, annual precipitation, and average relative humidity are between 270 and 278 days, between 900 and 1170 hours, between 1100 and 2600 mm, and 80%, respectively. Based on the division of thermal zones, obvious vertical band spectra can be witnessed, resulting in mid-subtropical, northern subtropical, southern temperate, and mid-temperate zones from the foot of Mount Fanjing to its top.

Materials and Methods

Soil Sampling and Preparation

Essential data on the soil surface layer in 1980 were primarily derived from the Fanjingshan Scientific Survey conducted in March 1980. Based on the description of the sample location of *A. fanjingshanensis* in the 1980 survey, soil samples were collected periodically at fixed points in the *Abies* forest of the Fanjingshan Nature Reserve in Guizhou. A 20 m×20 m square was set up to collect 1 kg of surface soil mixture sample beneath an *A. fanjingshanensis* forest. By selecting sufficiently mixed samples through quartering, 1 kg soil samples were set aside as the mixed samples at this point. Nine samples were collected separately in 1980, 2000, and 2020, for a total of 27 soil samples, as shown in Fig. 1. Collected soil samples were sent back to the laboratory for pretreatment determination.

Determination of Soil Samples

The content of soil organic matter was determined using the high-temperature external heating kalium dichromate oxidation-volume method; soil total nitrogen content and soil alkali hydrolysable nitrogen content were measured by the Kjeldahl nitrogen metre method; soil TP was determined using the acid-soluble-anticolorimetric determination of molybdenum and antimony; the available P content was determined using hydrochloric acid-ammonia fluoride extraction-anticolorimetric determination of molybdenum and antimony [16]; and soil particles were determined with the simple hydrometer method. All reagents adopted in the study were guaranteed reagents with deionized water. One blank sample was added for every 6 samples to ensure accuracy and the cleanliness of the reagents

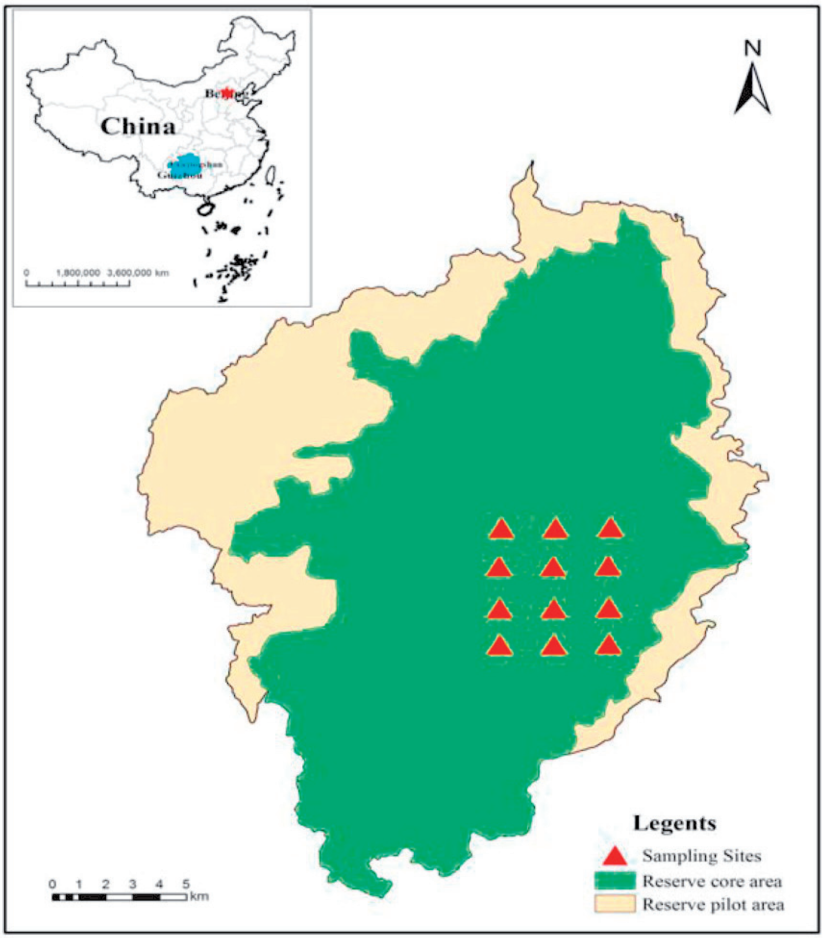

Fig. 1. Study area location and sampling point.

and containers. Moreover, 50% of the samples were randomly selected from each batch of samples to run in parallel. The relative deviation between samples was controlled within a limited range.

Data Analysis

The data were recorded in Microsoft Excel 2003, and the average value and correlation of each data were analysed by SPSS 18.0 software.

Results and Analysis

Soil Particle Characteristics in an *Abies fanjingshanensis* Forest

The soil grain size varied in different years, as shown in Fig. 2. The sand contents at a soil depth of 0-20 cm in 1980, 2000, and 2020 were 34.76%, 35.76%, and 47.78%, respectively, while the sand contents at a soil depth of 20-40 cm in 1980, 2000, and 2020 were 18.27%, 31.08%, and 33.38%, respectively. The silt content at a soil depth of 0-20 cm varied from 47.96% to 55.29% from 1980 to 2020. The silt content at a soil depth of 20-40 cm varied from 59.91% to 72.18% from 1980 to 2020.

In summary, the maximum sand content at a soil depth of 0-20 cm occurred in 2020, reaching 47.78%; the maximum silt content was found in 2000, reaching 56.74%; and the maximum clay and physical clay contents occurred in 1980, with values of 9.95% and 32.07%, respectively. At a soil depth of 20-40 cm, the maximum sand content was observed in 2020, reaching 33.38%, and the maximum silt, clay and physical clay contents occurred in 1980, at 72.18%, 9.55% and 53.07%, respectively. Evidently, the sand content gradually increased, while the clay content gradually decreased from 1980 to 2020. Increased soil porosity, strong ventilation and water permeability, poor water storage and fertilizer retention, and a tendency towards coarser grain sizes are caused by aggravative desertification in the soil beneath an *A. fanjingshanensis* forest.

Spatial-Temporal Variation in Soil Nutrients of *Abies fanjingshanensis*

Soil pH is an important indicator of acidity and is a crucial soil chemical property that strongly effects soil

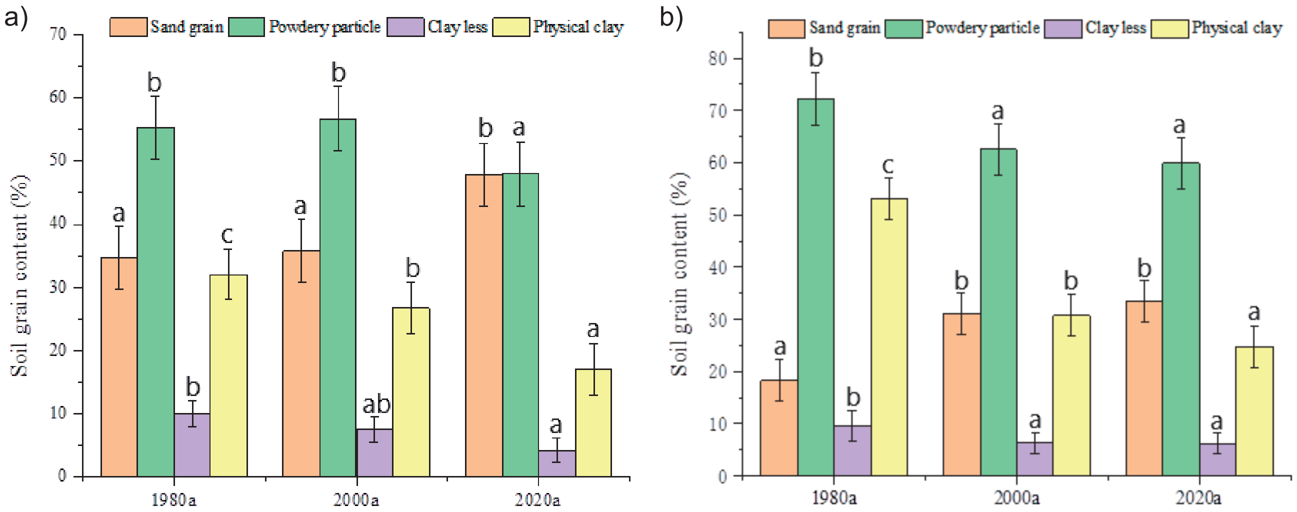

Fig. 2. The soil particle characteristics of *Abies fanjingshanensis* from 1980 to 2020; a) stands for 0~20 cm, Notes: Values followed by the same lowercase letters (a-c) are not significant. Difference of soil particle content of the same soil type in different years in 0-20 cm soil depth (P<0.05); The significance of this was determined by analysis of variance (ANOVA); b) stands for 20~40 cm, Notes: Values followed by the same lowercase letters (a-c) are not significant. Difference of soil particle content of the same soil type in different years in 20-40cm soil depth (P<0.05); The significance of this was determined by analysis of variance (ANOVA).

fertility. Soil pH values at different depths in different years varied, as shown in Table 1. The soil pH values at different depths and in different years ranged from 4.40 to 4.95. In addition, soil organic matter is a vital component of the solid phase of soil and an important factor for characterizing soil quality. With various nutrient elements required for plant growth, it is also an energy source for vital microorganism activities, which can directly affect and change a wide range of soil physical, chemical, and biological properties of the soil. The average organic matter content was high, with values of 23.025 g/kg in 1980, 26.525 g/kg in 2000 and 36.06 g/kg in 2020. The organic matter contents in different years were ordered 2020>2000>1980.

Overall, soil pH, soil organic matter, total nitrogen (TN), and available P increased at three time points in chronological order, while total phosphorus (TP), total kalium (TK), and rapidly available potassium changed insignificantly. Alkali-hydrolysable nitrogen showed a slow increasing trend. In addition, the cation exchange capacity (CEC) of the soil beneath the *A. fanjingshanensis* forest ranged from 19.67 cmol/kg to 56.79 cmol/kg, showing great variation. Alkaline hydrolysis nitrogen is available nitrogen that can be

Table 1. Spatial-temporal variation of soil nutrients of *Abies fanjingshanensis* (average±standard deviation).

Year	Thickness of soil	pH	Organic matter g/kg	TN g/kg	TP mg/kg	TK (g/kg)	AHN (mg/kg)	AP (mg/kg)	AK (mg/kg)	CEC (cmol/kg)
1980	0-20 cm	4.40 $\pm0.32^{a}$	23.88 $\pm3.12^{a}$	9.82 $\pm2.23^{b}$	0.19 $\pm0.02^{b}$	2.21 $\pm0.32^{b}$	452.12 $\pm22.21^{a}$	17.18 $\pm1.23^{a}$	157.11 $\pm34.12^{a}$	26.72 $\pm3.12^{b}$
	20-40 cm	4.50 $\pm0.28^{a}$	22.17 $\pm3.63^{a}$	6.95 $\pm3.23^{a}$	0.14 $\pm0.03^{a}$	1.87 $\pm0.23^{a}$	461.62 $\pm23.12^{a}$	16.13 $\pm1.73^{a}$	146.12 $\pm35.67^{a}$	19.67 $\pm3.43^{a}$
2000	0-20 cm	4.67 $\pm0.34^{ab}$	28.66 $\pm3.18^{a}$	16.05 $\pm2.65^{d}$	0.21 $\pm0.01^{c}$	2.32 $\pm0.25^{b}$	664.10 $\pm24.23^{b}$	30.24 $\pm3.21^{c}$	162.23 $\pm45.76^{ab}$	52.56 $\pm3.57^{c}$
	20-40 cm	4.72 $\pm0.26^{ab}$	24.39 $\pm1.23^{a}$	13.14 $\pm3.11^{c}$	0.18 $\pm0.02^{b}$	2.18 $\pm0.21^{b}$	674.10 $\pm27.51^{b}$	27.32 $\pm2.67^{bc}$	161.45 $\pm42.12^{ab}$	50.69 $\pm3.62^{c}$
2020	0-20 cm	4.91 $\pm0.27^{b}$	36.17 $\pm2.26^{b}$	18.74 $\pm1.87^{d}$	0.23 $\pm0.02^{c}$	2.35 $\pm0.28^{b}$	645.34 $\pm28.67^{b}$	24.70 $\pm3.65^{b}$	175.62 $\pm37.82^{b}$	53.26 $\pm4.12^{c}$
	20-40 cm	4.95 $\pm0.39^{b}$	35.95 $\pm3.12^{b}$	14.00 $\pm1.23^{c}$	0.21 $\pm0.01^{c}$	2.21 $\pm0.29^{b}$	682.86 $\pm28.76^{b}$	23.59 $\pm2.67^{b}$	181.72 $\pm38.56^{b}$	56.79 $\pm4.37^{c}$

Notes: TN is Total nitrogen, TP is Total phosphorus, TK is Total potassium, AHN is Alkali hydrolyzed nitrogen, AP is Available phosphorus, AK is Available potassium, And CEC is Cation exchange capacity. Values followed by the same lowercase letters (a-d) are not significant. The difference of the same soil nutrient in the same depth soil in different years (P<0.05); The significance of this was determined by analysis of variance (ANOVA).

absorbed and utilized by plants, which can sensitively indicate the nitrogen supply in soil. In this study, the content of alkali-hydrolysable nitrogen increased, meeting the nitrogen supply for *Abies* trees. According to the soil nutrients in 1980, 2000, and 2020, the soil organic matter, TN, TP, TK, and available P values in soil beneath the *A. fanjingshanensis* forest increased as the soil depth decreased, presenting surface accumulation. This is because utilization by animals and plants, as well as by soil microorganisms, declines in the process of transferring organic matter from the surface to the deep layer, resulting in the variation in soil nutrients.

Ecological Stoichiometry Characteristics of the Soil Beneath the *Abies fanjingshanensis* Forest

The ecological stoichiometric characteristics of soil beneath the *A. fanjingshanensis* forest vary, as shown in Fig. 3. Specifically, the C/P and N/P ratios of soil increased over time in the 0-20 cm soil layer, whereas the C/N ratio declined from 1980, to 2000 and 2020, reaching ratios of 2.43, 1.79 and 1.93, respectively. The C/N ratios in 1980, 2000, and 2020 at a soil depth of 20-40 cm were 3.19, 1.86, and 2.57, respectively. The C/N ratio reached its greatest value in 1980 and slightly decreased in 2020. The C/P ratios at a soil depth of 20-40 cm in 1980, 2000, and 2020 were 158.36, 135.5, and 171.19, respectively. The N/P ratios at a soil depth of 20-40 cm in 1980, 2000, and 2020 were 49.64, 73.00, and 66.67, respectively, reaching a maximum in 2000. Moreover, C/N changed insignificantly, while C/P and N/P changed significantly at the three time points.

Influencing Factors on the Ecological Stoichiometry of Soils Beneath the *Abies fanjingshanensis* Forest

The correlation between the soil mechanical composition and soil nutrients at the different time points was analysed, as shown in Table 2-4. Among them, the mechanical composition of 1~0.25 mm in 1980 was significantly positively associated with the pH and available P in the soil, as shown in Table 2. Soil mechanical compositions of 0.01~0.005 mm and less than 0.001 mm were significantly negatively associated with soil pH. A soil mechanical composition of less than 0.001 mm is significantly positively associated with alkaline hydrolysis nitrogen. As seen from the correlation in 2000 (in Table 3), soil mechanical compositions of 1-0.25 mm are significantly positively associated with available potassium, rapidly available potassium, and TP; soil mechanical compositions of 0.005 to 0.001 mm are significantly negatively associated with pH; and the physical clay content at the size of 0.001 mm is significantly positively associated with available P. Based on the soil mechanical

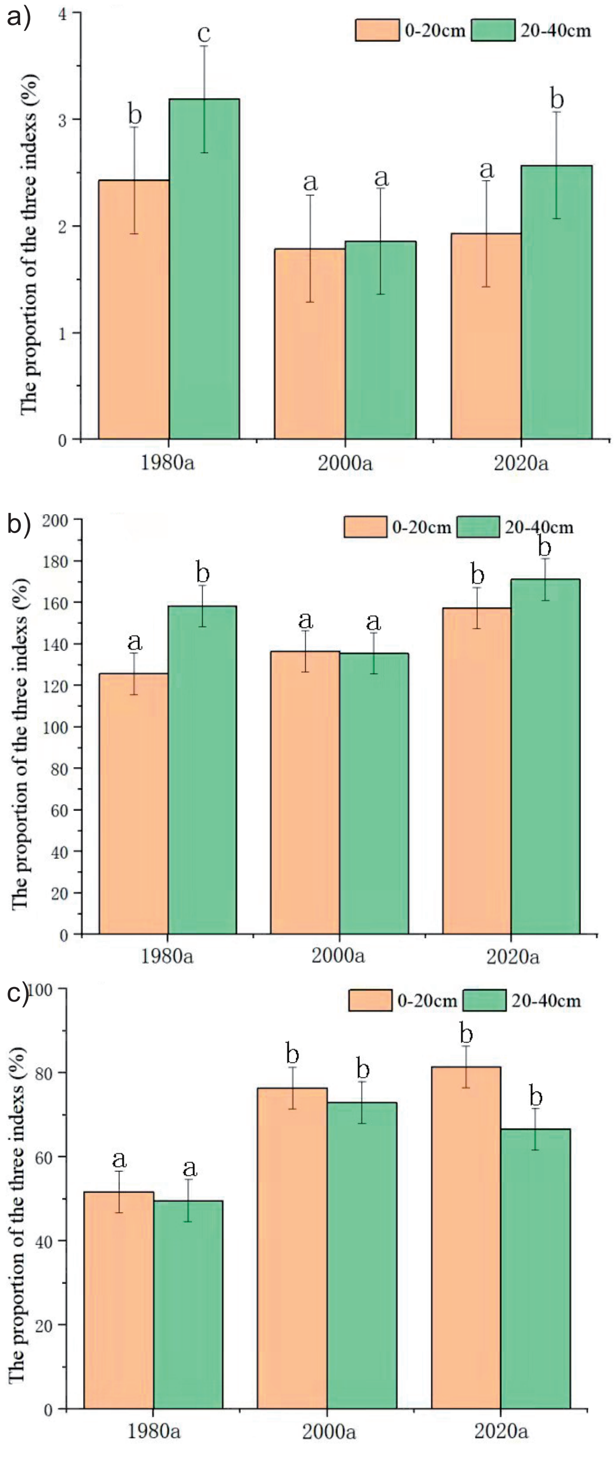

Fig. 3. Spatio-temporal evolution of Soil eco-chemical stoichiometry in *Abies fanjingshanensis;* a) stands for C/N, Notes: Values followed by the same lowercase letters (a-c) are not significant. The difference of soil C/N at the same soil depth in different years (P<0.05); The significance of this was determined by analysis of variance (ANOVA). b) stands for C/P, Notes: Values followed by the same lowercase letters (a-b) are not significant. The difference of soil C/P at the same soil depth in different years (P<0.05); The significance of this was determined by analysis of variance (ANOVA). c) stands for N/P), Notes: Values followed by the same lowercase letters (a-b) are not significant. The difference of soil N/P at the same soil depth in different years (P<0.05); The significance of this was determined by analysis of variance (ANOVA).

Table 2. Correlation analysis between soil mechanical composition and nutrients of Abies fanjingshanensis in different time (1980)

Particle size mm (%)	Soil nutrient								
	pH	OM	AHN	TN	AP	TP	AK	TK	CEC
1~0.25	0.61*	0.30	-0.26	0.25	0.67*	0.04	0.06	-0.25	0.17
0.25~0.05	0.16	-0.36	-0.29	-0.57	-0.45	0.40	-0.46	-0.06	-0.43
0.05~0.01	-0.28	-0.28	-0.06	-0.21	-0.06	-0.34	-0.02	-0.08	0.01
0.01~0.005	-0.68	-0.02	0.43	0.22	-0.44	-0.37	0.23	0.28	0.04
0.005~0.001	-0.35	-0.06	0.29	0.00	-0.13	0.10	0.45	0.23	0.24
<0.001	-0.76*	0.37	0.70**	0.54	-0.32	-0.15	0.19	0.48	0.16
Physical clay (<0.001)	-0.68*	0.13	0.60	0.31	-0.35	-0.17	0.33	0.39	0.16

Notes: OM is Organic matter, AHN is Alkali hydrolyzed nitrogen, TN is Total nitrogen, AP is Available phosphorus, TP is Total phosphorus, AK is Available potassium, TK is Total potassium, And CEC is Cation exchange capacity. ** Indicates that the correlation is significant when the confidence level (double measure) is 0.01; * the correlation is significant when the confidence level (double measure) is 0.05.

Table 3. Correlation analysis between soil mechanical composition and nutrients of *Abies fanjingshanensis* in different time (2000).

Particle size mm (%)	Soil nutrient								
	pH	OM	AHN	TN	AP	TP	AK	TK	CEC
1~0.25	0.69	-0.33	-0.49	0.62	-0.72	0.08	0.69*	-0.24	-0.42
0.25~0.05	-0.20	-0.10	0.64	0.06	0.48	0.85*	0.28	0.11	0.45
0.05~0.01	-0.06	0.62	-0.27	-0.28	-0.35	-0.61	-0.53	-0.38	0.02
0.01~0.005	0.22	0.32	0.68	-0.65	0.60	0.13	-0.26	-0.23	0.53
0.005~0.001	-0.95*	-0.33	-0.03	0.05	0.23	-0.01	-0.29	0.64	-0.21
<0.001	-0.46	-0.43	-0.75	0.38	-0.23	-0.51	-0.16	0.59	-0.62
Physical clay (<0.001)	-0.59	-0.11	0.28	-0.54	0.72*	-0.26	-0.66	0.56	0.08

Notes: OM is Organic matter, AHN is Alkali hydrolyzed nitrogen, TN is Total nitrogen, AP is Available phosphorus, TP is Total phosphorus, AK is Available potassium, TK is Total potassium, And CEC is Cation exchange capacity. ** Indicates that the correlation is significant when the confidence level (double measure) is 0.01; * the correlation is significant when the confidence level (double measure) is 0.05.

Table 4. Correlation analysis between soil mechanical composition and nutrients of Abies fanjingshanensis in different time (2020).

Particle size mm (%)	Soil nutrient								
	pH	OM	AHN	TN	AP	TP	AK	TK	CEC
1~0.25	-0.08	0.02	-0.19	-0.08	0.15	0.21	-0.07	-0.27	-0.18
0.25~0.05	-0.25	0.40	-0.02	0.48	0.28	-0.65	-0.13	-0.08	0.65
0.05~0.01	0.34	-0.37	-0.01	-0.58	-0.25	0.61	0.52	0.860*	-0.38
0.01~0.005	-0.66	-0.11	0.17	0.01	0.22	-0.58	-0.44	-0.09	0.33
0.005~0.001	0.06	-0.54	-0.22	-0.74	-0.02	0.50	-0.03	0.84*	-0.47
<0.001	0.55	-0.28	0.55	0.03	-0.74	0.16	0.12	-0.05	-0.37
Physical clay (<0.001)	0.46	-0.59	0.62	-0.25	-0.81*	0.20	-0.02	0.23	-0.52

Notes: OM is Organic matter, AHN is Alkali hydrolyzed nitrogen, TN is Total nitrogen, AP is Available phosphorus, TP is Total phosphorus, AK is Available potassium, TK is Total potassium, And CEC is Cation exchange capacity. ** Indicates that the correlation is significant when the confidence level (double measure) is 0.01; * the correlation is significant when the confidence level (double measure) is 0.05.

composition in 2020 (in Table 4), the soil mechanical compositions at particle sizes of 0.05~0.01 mm and 0.005~0.001 mm are significantly positively associated with TK, while physical clay less than 0.001 mm is significantly negatively associated with available P.

Discussion

Differences in Soil Carbon, Nitrogen and Phosphorus of *Abies's* Soil in Different Study Areas

Ecological stoichiometry characteristics of C, N, and P in the soil can reveal the availability of soil nutrients, nutrient cycling and balance mechanisms, which determines the relationship between soil nutrients and soil quality [17]. Globally, the stoichiometric ratio of C/N/P in the 0-10 cm soil layer is typically 186:13:1 (molar ratio), presenting significant stability. However, the ratio also fluctuates within a certain range, and can therefore vary to some degree [18]. As found from studies on the stoichiometric characteristics of C, N and P, C and N contents display large spatial variability, whereas the ratio of C to N is relatively stable and less affected by climate [19, 20]. The dynamics, diversity and spatial heterogeneity of soil nutrients can lead to variations in the stoichiometric characteristics of C, N and P in the soil of different ecosystems [21, 22]. N and P in the soil are the primary elements that help safeguard plant growth [23-25]. Moreover, since they are also indicators of the soil nutrient supply to the plant, their measurements impact plant growth [26, 27]. In addition, when N/P is less than 14, the plant will be N limited; when N/P is greater than 16, it will be P limited; and when N/P is between 14 and 16, it will be N/P limited [28, 29].

To evaluate the current nutrient element abundance and deficiency in *A. fanjingshanensis* soil, the data from this study were compared with the carbon, nitrogen and phosphorus contents of fir soil in other research areas (Table 5) [30-34]. Through comparison, it was found that the soil carbon, nitrogen and phosphorus of *A. fanjingshanensis* show different characteristics. The organic carbon and total phosphorus content are relatively low compared with other regions, and the available phosphorus content is moderate. The soil alkali hydrolysable nitrogen content is: *Abies fanjingshanensis* (645.34 mg/kg) >*Abies Minjiang* in Western Sichuan (179.25 mg/kg) >*Abies beshanzuensis* in Zhejiang (151.66 mg/kg) >*Abies odourifera* in Changbai Mountain, Jilin (85.81 mg/kg) >*Abies georgei* in Xizang (55.41 mg/kg), The total nitrogen content is: *Abies fanjingshanensis* (18.74 g/kg) >*Abies beshanzuensis* in Zhejiang (10.07 g/kg) >*Abies odourifera* in Changbai Mountain, Jilin (3.01 g/kg) >*Abies Minjiang* in Western Sichuan (2.01 g/kg) >*Abies georgei* in Xizang (0.05 g/kg). C/P and N/P ratios are high, and available phosphorus may be limited or even a restrictive factor for the growth of the *Abies fanjingshanensis* population.

Influencing Factors on the Ecological Stoichiometry of Soils Beneath the *Abies fanjingshanensis* Forest

Over time, the soil pH increased thereby increasing soil acidification, organic matter accumulation sharply increased in the later stage, the TN and alkaline hydrolysis nitrogen contents increased significantly, and available potassium also varied significantly. The increased cation exchange capacity in the soil indicates the enhanced preservation potential of *A. fanjingshanensis*. Moreover, the P content is normally proportional to the accumulation of soil organic matter, showing that the accumulation of organic matter has been increasing in the soil beneath the *A. fanjingshanensis* forest in the past 4 decades due to the differences in tree species. Moreover, soil microorganism and enzyme activities are suppressed at high altitudes and low temperatures, contributing to the accumulation of organic matter. The soil C/P of *A. fanjingshanensis* has fluctuated between 125.68 and 171.19 over the past 4 decades, which is far higher than the average soil C/P level (52.70) in China, indicating low P availability in the soil of this area. To summarize, plant residues, soil acidity, soil bulk density, and altitude

Table 5. Comparison of soil nutrient content of *Abies* in different regions.

Study Area	OC (g/kg)	TN (g/kg)	TP (g/kg)	AHN (mg/kg)	AP (mg/kg)	C/N	C/P	N/P
Abies beshanzuensis in Zhejiang	69.07	10.07	10.06	151.66	15.02	6.86	6.87	1.00
Abies nephrolepis in Jilin	10.9	3.01	0.86	85.81	14.30	3.62	12.67	3.50
Abies Minjiang in Sichuan	64.43	2.01	0.08	179.25	3.13	32.05	805.34	25.13
Abies georgei in Tibet	20.21	0.05	-	55.41	33.95	404.20	-	-
Abies fanjingshanensis (this study)	20.98	18.74	0.23	645.34	24.70	1.93	157.26	81.48

Notes: OC represents organic carbon, TN represents total nitrogen, TP represents total phosphorus, AHN represents alkali hydrolyzable nitrogen, AP represents available phosphorus.

seem to be important factors affecting the evolution of soil ecological stoichiometric characteristics. However, whether the above factors are essential in the evolution of the soil ecological stoichiometric characteristics of soils in *A. fanjingshanensis* forests should be further discussed.

Soil texture and particle size can indirectly affect soil ecological and chemical characteristics through soil fertility. For instance, clay soil with abundant nutrients can have a high organic matter content. In that case, most of the soil nutrients are obtained from rain and irrigation water, presenting favourable fertilizer-preserving performance. However, water cannot infiltrate the soil during rainfall or irrigation events, which might lead to difficult drainage, not only affecting the growth of roots but also blocking the root system's absorption of soil nutrients. According to this study, when the sand content in the soil beneath a *A. fanjingshanensis* forest increased, the silt content remained unchanged, while the clay and physical clay contents decreased. In addition, many studies have shown that soil C and N determine the distribution of the stoichiometric ratio of C, N, and P in the soil, while C/P and N/P are correlated to ammonium nitrogen, clay, sand contents, and water-stable macroaggregates in the soil as qualified in a significance test ($p<0.005$) [35-38]. Studies have also found that soil pH and soil bulk density exert significant effects on the stoichiometric characteristics of C, N, and P in the soil, while clay, silt and sand have insignificant effects. This result is consistent with the research of Cui Mingyanget al. [39] and Wang Shaoqiang et al. [40]. Over the years, SOC, TN, TP, dissolved organic nitrogen, the C:P ratio, the N:P ratio, and water content increased remarkably, whereas soil bulk density, available P and pH value decreased significantly. The results of the soil data correlation analysis are consistent with the research of Zhang Shaobo et al. [41-42]. There is a very significant positive correlation between soil total nitrogen and organic carbon content under a Abies fargesia forest in Fanjing Mountain and a very negative correlation between soil total phosphorus and organic carbon content.

Conclusion

The soil nutrients and ecological stoichiometry characteristics of soil beneath a *A. fanjingshanensis* forest in 1980, 2000 and 2020 were examined in this paper. The soil pH and organic matter, TN, TP, TK, alkaline hydrolysis nitrogen, and rapidly available potassium contents increased over the past 4 decades, while the available P first increased and then decreased. The C/P and N/P ratios in the surface soil of the *A. fanjingshanensis* forest are on the rise. The soil mechanical composition at a particle size of 1~0.25 mm in 1980 was significantly positively associated with the pH and available P of the soil, and soil mechanical compositions at sizes of 0.01~0.005 mm and less than 0.001 mm were significantly negatively associated with soil pH. The soil mechanical composition at a size of 1-0.25 mm in 2000 was significantly positively associated with rapidly available potassium and TP, while the soil mechanical composition at a size of 0.005 to 0.001 mm was significantly negatively associated with soil pH. In 2020, the soil mechanical compositions at particle sizes of 0.05~0.01 mm and 0.005~0.001 mm were significantly positively associated with TK, while physical clay less than 0.001 mm is significantly negatively associated with available P. Overall, P in the soil is a significant factor restricting the growth of *A. fanjingshanensis*.

Acknowledgments

This work was supported by the Guizhou forestry scientific research project (No. [2020] 02); the Youth fund of Guizhou Academy of Sciences.(No. [2021] 13) and the Guizhou science and technology support plan project (No. [2020] 1Y178).

Conflict of Interest

The authors declare no conflict of interest.

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