VARIATION OF PLANT COMPOSITION AND SOIL ORGANIC CARBON OF FOREST WITH INCREASE OF ALTITUDE IN GUIZHOU PROVINCE, SOUTHWEST CHINA

HONG, J. [1#] – LU, B.[2#] – WANG, X. F.[3] – WAN, H. F.[1] – HUANG, X. F.[2*]

[1]*Guizhou Academy of Sciences, Guiyang, Guizhou 550001, China*

[2]*Guizhou Provincial Key Laboratory for Environment, Guizhou Normal University, Guiyang, Guizhou 550025, China*

[#]*Co-first authors*

**Corresponding author*
e-mail: hxfswjs@gznu.edu.cn

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Abstract. Soil organic carbon is critical in mediating global climate change and maintaining soil fertility. The impact of the altitude on the soil carbon of karst forests has not been fully studied yet. In this study, variation of plant composition and soil organic carbon (SOC) content of forest in Guizhou Province of China were studied based on field investigation and laboratory analysis. The results suggested that forests in low altitude (<500 m) and high altitude (>2000 m) were mainly pure forests, and plant diversity in forests of these regions were low in Guizhou Province. Along with the increase of altitude, the mean contents of SOC increased from 17.28 ± 3.27 g/kg to 45.13 ± 7.16 g/kg. The SOC contents presented significant positive correlations with altitude ($r = 0.394$, $P < 0.001$), soil moisture ($r = 0.570$, $P < 0.001$), total phosphorus (TP) ($r = 0.438$, $P < 0.001$) and available phosphorus (AP) ($r = 0.275$, $P < 0.01$), and presented significant negative correlations with rock outcrop ($r = -0.200$, $P < 0.05$) and total potassium (K) ($r = -0.285$, $P < 0.01$). It is concluded that temperature, soil moisture and phosphorus may be the main factors affecting forest species composition and SOC contents.
Keywords: *altitude, soil organic carbon, forest land, plant composition*

Introduction

Karst areas are unique ecosystems that differ from non-karst areas in terms of terrain and landforms because of the special geological and climatic conditions that lead to karst mountainous areas exhibiting low environmental capacity, low stability and poor self-regulation (Wang et al., 2020; Zheng et al., 2016). The karst landform accounts for, approximately, 15% of the global land area, and karst landforms are widely distributed in southern China as well (Fleury et al., 2013). In China, it is about 3.44 million km^2, accounting for more than 1/3 of the national land area (Song et al., 2017). Guizhou province is the center of contiguous area in Southwest China Karst, the karst landform accounts for about 73.7% of the total land area (Zhang et al., 2018). The main composition of rock in karst areas is carbonate rocks, and carbonate is the largest reservoir of carbon storage in the world (Wang et al., 2020; Yuan, 2001). According to the statistics on the global organic carbon stock, the soil organic carbon (SOC) stock in 0-100 cm soil layer is reach to 1460 Pg, which is two times and three times greater than vegetation and atmosphere carbon reserve (Weissert et al., 2016). So, SOC play an important role in the global carbon cycle. These result in a small change in SOC may lead to a huge change in atmospheric CO_2 concentration (Wang et al., 2021).

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Guizhou experienced severe contradiction between humans and the environment from fifties to nineties of twenty century. A large amount of forestland and grasslands were reclaimed for croplands to solve the starvation problem temporarily. These make the rocky desertification is serious problem in Guizhou province (Huang et al., 2022). Noticeable adverse effects of deforestation and infrastructure development on the environment has become a serious problem globally. Atmospheric carbon dioxide increased and serious setbacks like global warming and climate change occurred (Kumari et al., 2022). During the past twenty years, the rural economic structure in Guizhou Province has improved dramatically. The forest coverage rate continuously increased (From 30.83% in 2000 to 62.81% in 2022) under the guidance and regulation of central, provincial and local governments. Forest soils are a great carbon stock, and are playing a pivotal role in global carbon cycle (Zhang et al., 2019; Carvalhais et al., 2014; Liu et al., 2024). Forest soils are considered effective carbon sinks, potentially stabilizing a large amount of organic carbon depending on the balance between net primary production and soil carbon mineralization rate (Andreetta et al., 2023). SOC is the carbon in soil organic matter, which comprise plant and animal residues in different stages of decomposition, soil microbial cells and tissues and substances generated by soil microorganisms (Zhao et al., 2023). SOC is critical in mediating global climate change and maintaining soil fertility (Huang et al., 2018). The spatial distribution of SOC in karst landforms is complex. It is mainly influenced by species composition, soil properties, and environmental factors, and the dominant influencing factors in different regions are different. Recently, increasing attention is attracted by the relationship between altitude and soil organic carbon (Chimdessa, 2023).

Altitude is a key factor affecting the content of SOC and the plant composition of forestland, consequently affecting the soil microbial composition and abundance which playing a critical role in nutrient cycling of the ecosystem. Some studies reported that SOC increased along with altitude. Qiu et al. (2022) found that there were some positive correlations existed between SOC content and altitude ($R^2 = 0.174$, $p < 0.01$). In high-altitude areas, the temperature is relatively low, plant metabolism is slow, bacterial activity is weakened, and organic matter decomposition rate is slow, resulting in an increase in organic matter content. In addition, soils in high-altitude areas has poor aeration, and anaerobic conditions are not conducive to the decomposition of organic matter, resulting in an increase in organic matter content as well. In lower-altitude areas, above- and below-ground biomass and litter carbon were higher due to higher biomass production resulted from higher photosynthesis and higher net primary production (Chen et al., 2023). First, altitude determines the plant composition of forest land which closely associated with the input amount and quality of organic matter; secondly, altitude determines the soil water property which could be an important factor impacting on both accumulation and decomposition of the SOC (Liu et al., 2023a; Zeng et al., 2019). In addition, the altitude effect on microbial activity, their residue carbon plays a significant role in the formation and stabilization of soil carbon pools (Sun et al., 2023; Butlers et al., 2022).

However, there is lack a report about altitude effecting on plant component and SOC spatial heterogeneity in karst mountainous area (Huang et al., 2022). The altitude of Guizhou province ranged from 147.80 m to 2900.60 m above the sea level. Therefore, it is of great importance to measures the SOC increase in forestland with the change of altitude. The relationship between altitude, plant composition and SOC were unclear. If the altitude influences plant composition, as different plants are adapted to different

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altitudinal zones, changes in plant composition with altitude can affect the quality of litter input (e.g., leaf litter, roots). This variation affects the type and amount of organic matter contributed to the soil, influencing SOC dynamics through variations in decomposition rates and nutrient content. Or, at higher altitudes, temperatures are generally cooler, which can slow down the decomposition rates of organic matter, leading to higher SOC accumulation. So, the main objectives of present study was: (a) to study the variation of plant composition and SOC contents of forestland along with altitude increase; and (b) to explore directly/indirectly factors affecting SOC contents in Guizhou Province. We hope this research could provide some scientific information in improvement of carbon sink in forestland globally.

Experimental

Study area

Guizhou Province is located in the the Yunnan-Guizhou Plateau, between 103°36′-109°35′ E and 24°37′-29°13′ N, bordering Hunan in the east, Guangxi in the south, Yunnan in the west, Sichuan and Chongqing in the north. The total area is 176,167 km^2, accounting for 1.8% of the national area China. Guizhou is a typical Karst region with severe rocky desertification problem (Yang et al., 2023). In this region, the mountains and hills account for 97% of the total area, and the Karst landform distributed in 95% of the counties (Zhang et al., 2021). Due to the unique landform, geographical environment characteristics (such as slope, slope position, altitude and vegetation) are very complex (Huang et al., 2019). The mean annual temperature and mean annual precipitation were approximately 15.0°C and 1000-1400 mm, respectively. The main soil types in study region includes sandy soil, yellow soil, yellow-red soil, alpine meadow soil and limestone soil. The main ecosystem types in the study area include montane elfin forest, coniferous and broadleaved mixed forest and evergreen broad-leaved forest (Huang et al., 2018).

Field investigation and soil sampling

Field investigation and soil sampling was carried out during the period from 8th, June to 15th, August in 2023, and a total of 139 sampling points were sampled (*Fig. 1*). To avoid the influence of subjective factors, the sub-sampling regions were designed with aids of geographic information system. For each sub-sampling region, three to seven sampling plots were selected randomly. At each sampling spot, soils (0-20 cm) were collected at five sites around sampling plot and mixed as the final sample. The soil bulk densities (SBD) was determined in the field [18]. In this study, sampling plots were divided into five groups according to their altitude: group I < 500 m, 500 m ≤ group II < 1000 m, 1000 m ≤ group III < 1500 m, 1500 m ≤ group IV < 2000 m, and 2000 m ≤ group V.

Analytical procedure

Soil properties including pH, SOC and some elements (includes Ca, K, Mg, Na, P and AP) were analyzed in laboratory. To determine the soil pH, 10 g soil samples (air dried) were weight, and 25 ml deionized water was added, and then a pH meter was put into the suspension to determine the soil pH after stirring thoroughly. The contents of SOC were determined by an oxidation capacity test with $K2Cr_2O_7$ and external heating

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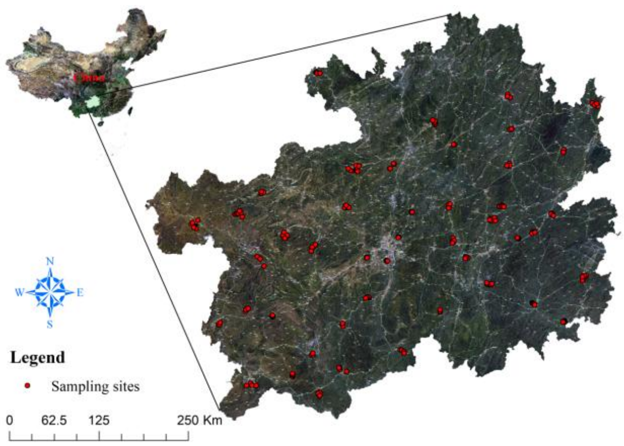
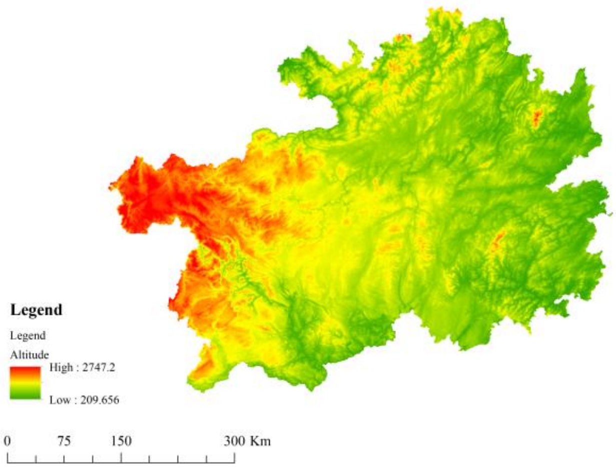
(Nelson, 1982; Huang et al., 2019). Soil total phosphorus (TP) were tested according to a protocol developed by the Standard Measurements and Testing Program of the European Commission was applied (Ruban et al., 2001; Jiang et al., 2011). For analysis of available phosphorus (AP), 1.0 g soil was extracted with 100 mL 0.5 M $NaHCO_3$. The pH was adjusted to 8.5, by shaking end-over-end for 16 h. Extracts were filtered and AP was then measured, after color development based on the molybdate blue method (Haert and Cirbsnand, 2012). To analyzing the contents of K, Na, Ca and Mg, 0.5000 g of soil sample was weighed accurately into a 150-ml tetrafluoroethylene digestion tank, 0.5 ml of deionized water was added to moisten the soils, and then 20 ml of digesting mixture made up of conc. hydrofluoric acid, conc. nitric acid and conc. perchloric acid (3:4:1 (V/V/V)) was added. The tetrafluoroethylene digestion tanks were placed on an electric heating plate, and heated with low temperature for ca. 60 min, then the electric heating plate was adjusted to the highest temperature (about 220℃), and the heating was continued until a small amount of solution (about 0.5 ml) was left and the solution becomes clear. The left solution was transferred into 50-ml volumetric flask and diluted to the full volume with 0.5% (V/V) nitric acid solution. The solutions prepared above were used to determinate K, Na, Ca and Mg using inductively coupled plasma-optical emission spectrometer (ICP-AES).



(a)



(b)

Figure 1. *Distribution of sampling sites (a) and digital elevation model of Guizhou Province (b)*

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Statistical methods and software

Structural equation modeling (SEM), it is when need to explore complex relationships among multiple variables, including direct and indirect effects. SEM facilitates hypothesis testing about the relationships and the structure of the model, offering indices to evaluate model fit. Random forests can model complex, non-linear relationships without needing data transformation. The algorithm is tolerant of missing data and noise, making it versatile for real-world datasets. Using SEM and Random Forest together can be particularly powerful. SEM helps in understanding theoretical relationships and confirming models, while Random Forest offers robustness and exploratory power to detect patterns and variable importance, which can further inform and refine the SEM. This complementary approach allows for a comprehensive understanding of the data from both confirmatory and exploratory perspectives.

In present study, data management, analysis and visualization were conducted with software programs such as ArcGIS 10.2, Excel 2016, SPSS 20.1, R for Windows 3.5.1, Origin 2021, USEARCH 10.0, QIIME 1.8.0, and Cannon 5.0.

Results and discussion

Soil physi-chemical properties and SOC contents

Soil types in group I were mainly yellow soil and sandy soil; group II: yellow soil, yellow-red soil and limestone soil; group III: yellow soil, yellow-red soil, limestone soil; group IV: yellow soil, yellow-red soil, limestone soil; and group V: alpine meadow soil. As listed in *Table 1*, no significant ($p > 0.05$) variation of pH value was found among different groups based on mean value. The SBD of group V was 0.87 ± 0.15 which was significantly ($p < 0.05$) lower than that of the other groups. Soil moisture increased along with altitude from $22.94 \pm 1.89\%$ to $33.23 \pm 2.50\%$. For SOC contents, the boundary line was at an altitude of 1500 m. The SOC contents of forest land below 1500 m were significantly ($p < 0.05$) lower than those of forest land above 1500 m. The variation trend of total phosphorus (P) contents with altitude was similar to that of SOC. There is no significant ($p > 0.05$) difference in the P contents of forestland soils below 1500 m. The P content in the soils of forestland above 1500 m was significantly ($p < 0.05$) greater than that of forests below 1500 m. The variation trend of soil available phosphorus (AP) in forestland with altitude increase was consistent with that of P, but there is no significant ($p < 0.05$) difference in forestland soil AP among different groups.

Along with the increase altitude, the soil Ca contents in forestland showed a trend of first increasing, then decreasing, and finally increasing again (*Fig. 2*). Below 1500 m, the soil K contents in forestland were uniform and there was no significant ($p > 0.05$) variation between different altitude ranges. The soil K contents in forestland above 1500 m showed a weak downward trend, but there was no significant ($p > 0.05$) difference between the soil K contents in forestland with altitude ranged from 1500 to 2000 m and above 2000 m. The distribution of soil Mg contents in forestland with increasing altitude was similar to that of soil K content, but there was no significant ($p > 0.05$) difference in soil Mg contents between forestland at different altitudes above 500 m. The soil Na contents in forestland showed a trend of first decreasing and then increasing with the increase of altitude. At the same time, there were some significant ($p < 0.05$) differences in soil Na contents between forestland below 1000 m and above 1000 m in altitude.

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Table 1. *Physical and chemical properties*

Groups	Number of plots	pH Value	Soil bulk density (g/cm^3)	Soil moisture (%)	SOC (g/kg)	TP (mg/kg)	AP (mg/kg)
I	12	6.38 ± 0.27a	0.99 ± 0.12b	22.94 ± 1.89ab	17.28 ± 3.27a	391.05 ± 67.52a	12.76 ± 7.42a
II	48	6.23 ± 0.16a	0.97 ± 0.11b	22.57 ± 0.94a	20.16 ± 2.09a	347.94 ± 30.49a	10.99 ± 2.81a
III	42	6.49 ± 0.21a	1.03 ± 0.09b	23.69 ± 0.72ab	19.01 ± 1.70a	344.91 ± 29.05a	10.95 ± 1.21a
IV	26	6.49 ± 0.20a	1.01 ± 0.11b	26.18 ± 2.06b	39.16 ± 7.50b	608.90 ± 77.14b	16.19 ± 3.69a
V	11	6.37 ± 0.09a	0.87 ± 0.15a	33.23 ± 2.50c	45.13 ± 7.16b	1062.88 ± 156.88c	18.19 ± 3.81a
Total	139	6.38 ± 0.27	0.97 ± 0.14	24.50 ± 0.67	25.41 ± 2.04	459.86 ± 31.07	12.72 ± 1.43

In the same column, values followed by the same lowercase letter were not significantly ($p < 0.05$) different between groups

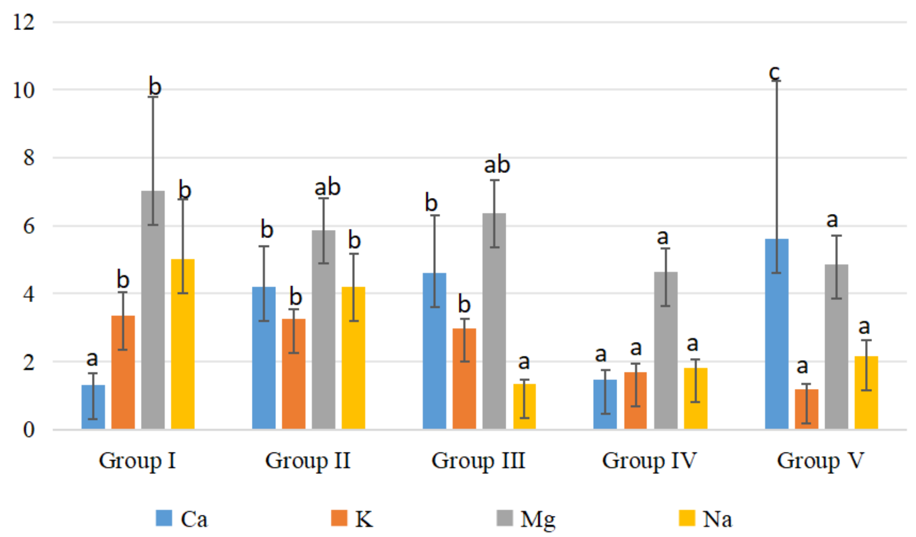

Figure 2. *Contents of Ca, K, Na and Mg in soil samples collected from different altitude ranges ($\times 10^3$ mg/kg)*

Varieties of trees and herbs under different altitude

Based on field investigation, a total of 3 Phylum (Angiospermae, Gymnospermae, and Pteridophyta), 4 Classes (Dicotyledoneae, Monocotyledoneae, Coniferopsida, and Filicopsida), 26 order (Campanulales, Contortae, Ericales, Euphorbiales, Fagales, Geraniales, Juglandales, lantaginales, Myrtiflorae, Parietales, Polygonales, Primulales, Ranales, Rhamnales, Rosales, Rubiales, Rutales, Sapindales, Tubiflorae, Umbelliflorae, Urticales, Graminales, Liliflorae, Principes, Pinales, and Eufilicales), 49 families, 86 genus and 97 species (*Table A1*) were recorded.

In the present study, plants found in Group I (altitude < 500 m) include, a total of 3 Phylum (*Angiospermae*, *Gymnospermae*, and *Pteridophyta*), 4 Class (*Dicotyledoneae*, *Monocotyledoneae*, *Coniferopsida*, and *Filicopsida*), 12 Order (*Campanulales*, *Contortae*, *Fagales*, *Ranales*, *Rosales*, *Sapindales*, *Umbelliflorae*, *Graminales*, *Liliflorae*, *Principes*, *Pinales* and *Eufilicales*), 18 Family, 21 Genus and 21 Species; Group II (500 ≤ altitude < 1000 m): 3 Phylum (*Angiospermae*, *Gymnospermae*, and *Pteridophyta*), 4 Class (*Dicotyledoneae*, *Monocotyledoneae*, *Coniferopsida*, and *Filicopsida*), 20 Order (*Campanulales*, *Contortae*, *Euphorbiales*, *Fagales*,

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Juglandales, Myricales, Parietales, Primulales, Ranales, Rosales, Rubiales, Rutales, Sapindales, Tubiflorae, Urticales, Graminales, Principes, Scitamineae, Pinales, and *Eufilicales*), 33 Family, 49 Genus and 49 Species; Group III (1000 ≤ altitude < 1500 m): 3 Phylum (*Angiospermae*, *Gymnospermae*, and *Pteridophyta*), 4 Classis (*Dicotyledoneae*, *Monocotyledoneae*, *Coniferopsida*, and *Filicopsida*), 23 Order (*Campanulales, Contortae, Euphorbiales, Fagales, Juglandales, Myrtiflorae, Parietales, Polygonales, Primulales, Ranales, Rhamnales, Rosales, Rubiales, Rutales, Sapindales, Tubiflorae, Umbelliflorae, Urticales, Graminales, Liliflorae, Principes, Pinales,* and *Eufilicales*) 40 Families, 61 Genus and 66 Species; Group IV (1500 ≤ altitude < 2000 m): 3 Phylum (*Angiospermae*, *Gymnospermae*, and *Pteridophyta*), 4 Classis (*Dicotyledoneae*, *Monocotyledoneae*, *Coniferopsida*, and *Filicopsida*), 17 Order (*Campanulales, Ericales, Fagales, eraniales, Juglandales, Myrtiflorae, Parietales, lantaginales, Polygonales, Ranales, Rosales, Rutales, Sapindales, Tubiflorae, Graminales, Pinales, and Eufilicales*) 29 Families, 41 Genus and 43 Species; Group V (2000 ≤ altitude): 3 Phylum (*Angiospermae*, *Gymnospermae*, and *Pteridophyta*), 3 Classis (*Dicotyledoneae*, *Coniferopsida*, and *Filicopsida*), 5 Order (*Campanulales*, *Fagales*, *Tubiflorae*, *Pinales*, *and Eufilicales*) 5 Families, 6 Genus and 6 Species. Clearly, forests in low altitude (<500 m) and high altitude (>2000 m) were mainly pure forests, and plant diversity in forests of these regions were low in Guizhou Province.

Relationships of SOC and soil physio-chemical indices

According to Pearson correlation coefficients (*Fig. 3a,b*), SOC was significantly correlated with altitude ($r = 0.394$, $p < 0.001$), moisture ($r = 0.570$, $p < 0.001$), P ($r = 0.438$, $p < 0.001$), AP ($r = 0.275$, $p < 0.01$), rock outcrops ($r = -0.200$, $p < 0.05$), K ($r = -0.285$, $p < 0.01$). Altitude was significantly correlated with K ($r = -0.373$, $p < 0.001$), Na ($r = -0.295$, $p < 0.01$), P ($r = 0.521$, $p < 0.001$). In addition, significant correlation also found between slope gradient and rock outcrops ($r = 0.270$, $p < 0.01$), between altitude and moisture ($r = 0.344$, $p < 0.001$), between Na and Mg ($r = 0.369$, $p < 0.001$), between rock outcrops and pH ($r = 0.290$, $p < 0.01$), between K and Mg ($r = 0.466$, $p < 0.001$), between K and Na ($r = -0.232$, $p < 0.05$), and between K and AP ($r = -0.256$, $p < 0.05$). In order to reveal the altitude effecting on SOC, the correlation between altitude and SOC was analyzed (*Fig. 3c*). The altitude was divided into five levels, and the SOC content increased rapidly between 1000 and 2000 m. The rate of SOC content increase is relatively slow both below 1000 m and above 2000 m. In addition, there was a positive correlation between SOC and phosphorus, the correlation index r is 0.26 ($p < 0.05$) (d).

Discussion

In Guizhou Province, the mean SOC content of forestland was 25.41 ± 2.04 g/kg. Compared with those in other regions of China (8.21-97.14 mg/kg), the SOC content in forestland in Guizhou Province (17.28-45.13 mg/kg) was intermediate (*Table 2*). It is clear that altitude is an important geographic factor that indirectly influences forest SOC content, and this result is highly consistent with previous reports (Huang et al., 2022). The SOC contents of soil at high altitudes were greater than those in middle- and low-altitude areas and reached a maximum value at or near the top of the mountain (Huang et al., 2023).

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There is usually a relationship between altitude and temperature: the higher the altitude is, the lower the temperature. The direct heat source for the tropospheric atmosphere is the ground; the farther away from the ground, the less ground radiation is received, and the lower the temperature. Previous research has indicated that the ambient temperature decreases by 0.54°C to 0.58°C for every 100 m of elevation (Rolland et al., 2003). Temperature plays a vital role in the reproduction and growth of plants and is one of the main factors affecting forest plant species composition and community structure (Huang et al., 2024). Forest plant species composition and community structure directly determine the input quality of forest organic matter. In the present study, 3 phyla, *Angiospermae*, *Gymnospermae*, and *Pteridophyta*, were detected in all the groups. Four classes, including *Dicotyledoneae*, *Monocotyledoneae*, *Coniferopsida*, and *Filicopsida*, were recorded in regions with altitudes lower than 2000 m, and *Monocotyledoneae* was not observed in regions with altitudes greater than 2000 m. For Groups II, III and IV, whose altitudes ranged from 500 m to 2000 m, the plant diversity was obviously greater than that of Group I and Group V. First, the forests in Groups I and V were mainly pure forests, and the plant diversity in the forests of these regions was low. In addition, the areas with altitudes below 500 m and above 2000 m occupied relatively small areas, and the number of investigated sampling points was relatively small. Temperature, to a certain extent, determines the community structure and abundance of soil microorganisms, consequently affecting organic matter degradation and microbial carbon quantity and quality. Microbes are decomposers in soil systems and regulate the turnover of nonmicrobially sourced carbon, contributing to the formation of microbially sourced carbon (Liang and Zhu, 2021; Shao et al., 2022).

Table 2. *SOC content in forestland soil (0-10 cm) in China*

Locations	Altitude (m)	Min. (g/kg)	Max. (g/kg)	Mean (g/kg)	References
Taian, Shangdong	629-940	10.29	29.64	20.38	Zhang et al., 2015
Aohanqi, Neimeng	440-906	—*	—	8.21 ± 0.59	Wang et al., 2014
Changsha, Hunan	100-550	13.25	42.65	—	Wang et al., 2018
Meizhou, Guangdong	629-940	0.88	34.94	8.41	Zhang et al., 2022
Sanxia, Chongqing	350-950	12.06	45.18	18.35	Wang et al., 2010
Ziwuling, Shanxi	1280-1500	3.90	37.60	34.99 ± 4.1	Yang et al., 2010
Heihe, Qinghai	3105-3479	—	—	97.14 ± 4.23 (Coniferous forest)	Wang et al., 2015
		—	—	68.81 ± 3.86 (Forest thickets)	
		—	—	53.37 ± 3.24 (Broadleaved forest)	
Xuanwei, Yunnan	920-2868	—	—	54.37 ± 2.06	Li et al., 2017
Guizhou Province	221-500	3.72	33.54	17.28 ± 3.27	This study
	500-1000	3.62	78.87	20.16 ± 2.09	
	1000-1500	5.59	43.10	19.01 ± 1.70	
	1500-2000	5.35	148.25	39.16 ± 7.50	
	2000-2378	16.44	90.96	45.13 ± 7.16	
	221-2378	3.62	148.25	25.41 ± 2.04	

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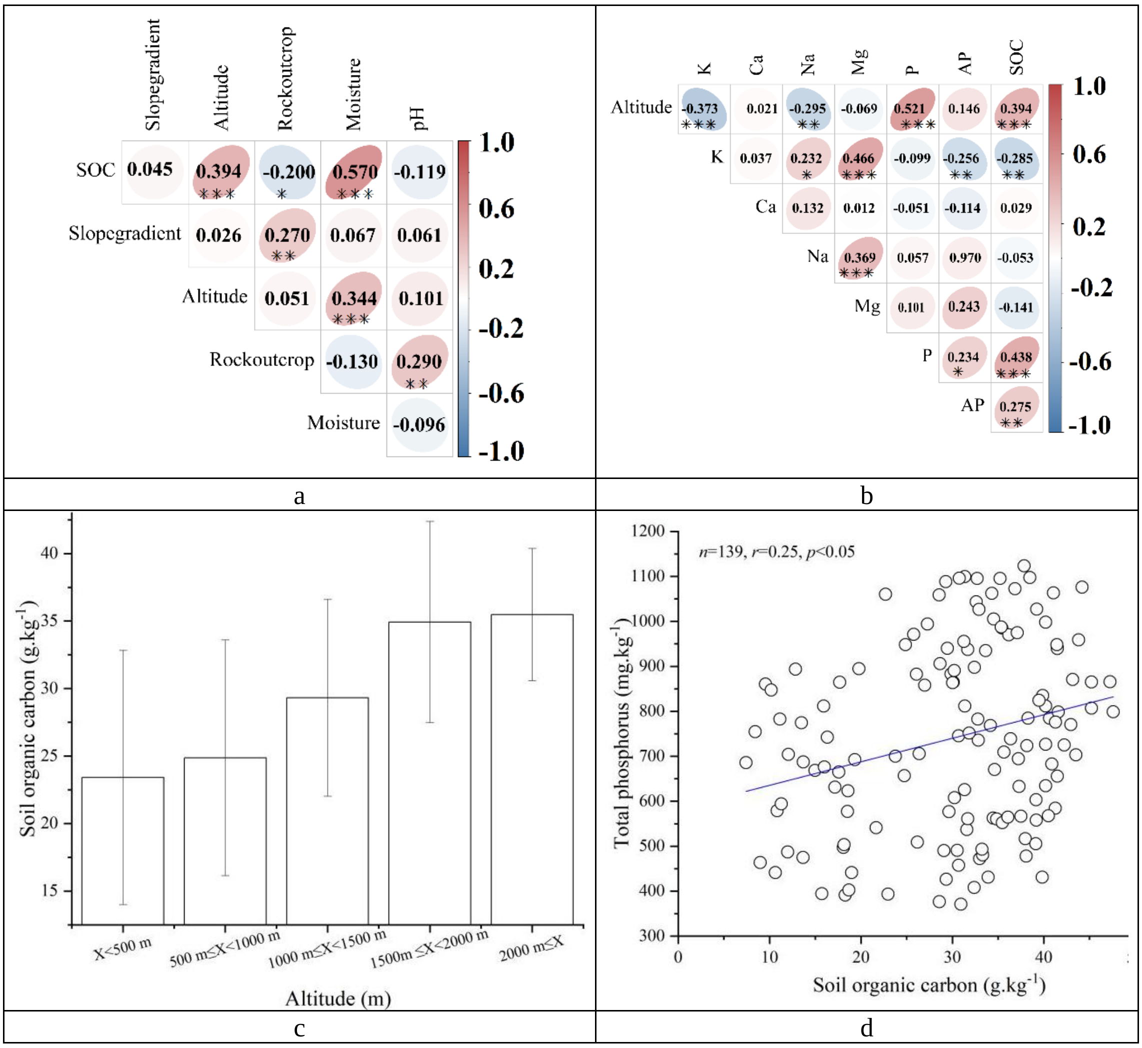

Figure 3. *Pearson correlations between SOC and geographic factors (a); and between SOC and nutrient elements (b) (***correlation is significant at the 0.001 level (2-tailed); **correlation is significant at the 0.01 level (2-tailed); *correlation is significant at the 0.05 level (2-tailed)); and the relationship between SOC and altitude (c); and the relationship between SOC and phosphorus (d)*

On the basis of the Pearson correlation analysis, geographic factors (slope gradient, slope position, altitude, rock outcrops, moisture, pH, niche and soil moisture content) and nutrient elements (Ca, K, Na, Mg, P and AP) were selected as the latent variables in the structural equation model. The effects on the SOC in forestland soils were taken as the output value to establish the structural equation conceptual model (SECM). Through the data fitting of Amos 22.0, the evaluation indices and path coefficients of the model were obtained. The Chi square/degrees of freedom of the model is 1.86 (<3), indicating that the fitting degree of the model is good (Wu et al., 2023). The random forest method analysis, which is an ensemble learning algorithm method that uses decision trees as base learners, was also carried out, as presented in *Figure 4*. According to the structural equation conceptual model, the soil moisture content was the key factor influencing the SOC content. There was a positive correlation between the SOC content in the SECM and the soil moisture content, P, AP, and pH in soil, while only a weak negative

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correlation existed between SOC and altitude. There were strong positive impacts between altitude and soil moisture content and a negative relationship between rock outcrops and soil moisture content. According to the random forest method analysis (*Fig. 5*), factors influencing SOC in forestland soils in Guizhou Province are arranged in descending order as follows: soil moisture > AP > altitude > P > pH > K > slope gradient > Mg > Na > Ca > slope position > rock outcrop > niche > soil properties.

According to both the structural equation conceptual model and random forest method analysis, soil moisture is the primary factor influencing SOC in forestland soils in Guizhou Province. This result is in good agreement with those of several previous studies. Liu et al. (2009) conducted an experiment concerning soil and microbial respiration and microbial biomass in response to warming and precipitation on a semiarid temperate steppe in northern China, and their results suggested that soil moisture is more important than temperature in regulating microbial biomass on the semiarid temperate steppe. In addition to soil moisture, AP is also an important factor influencing the SOC content in forestland soils in Guizhou Province. Phosphorus is the main component of phospholipids and an essential element in cell membranes. It is also an important precursor for a series of intermediates with strong biological activity in biological metabolism and physiology, such as eicosane-like acids and phosphoinositol. Phosphorus is an essential mineral in many biochemical processes in living organisms and plays an important role in their growth and development (George et al., 2016). SOC and P in soil have a synergistic relationship, each promoting the accumulation of the other (Wang et al., 2018). Phosphorus is crucial for plant growth, as it supports photosynthesis and energy transfer. Healthy plants generate more biomass, which decomposes into organic carbon, enhancing the SOC pool. SOC, in turn, improves soil structure, water retention, and nutrient availability, including P. Moreover, P is vital for soil microbial metabolism, which in turn influences the breakdown of organic matter into SOC. Adequate P boosts microbial activity, leading to a more efficient breakdown of organic matter and SOC formation. Moreover, an increase in SOC fosters microbial diversity and function, improving P mineralization and availability. Therefore, P, especially AP is an important factor that determines the diversity and abundance of soil organisms (bacteria, fungi, protozoa, etc.) and consequently influences soil organic carbon accumulation (Gu et al., 2023; Liu et al., 2023b). This creates a positive feedback loop: P availability promotes plant growth and microbial efficiency, leading to SOC accumulation, which further enhances nutrient cycling.

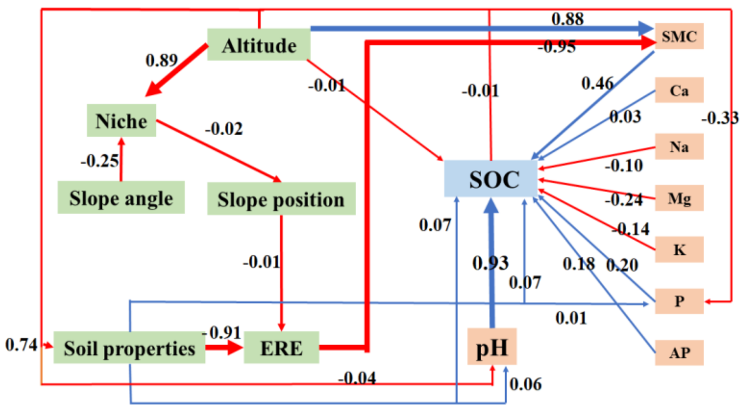

Figure 4. *The structural equation conceptual model of SOC in forestland soils in Guizhou Province (SMC and ROC represent the soil moisture content and rock outcrops, respectively)*

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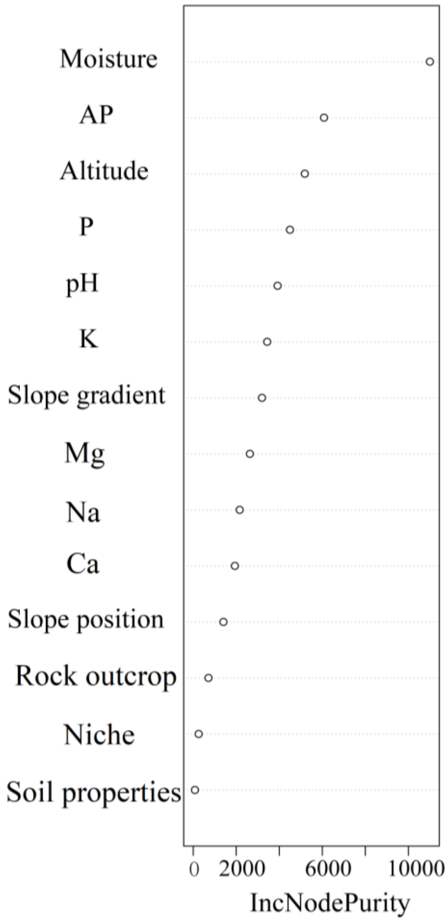

Figure 5. *Factors influencing SOC in forestland soils in Guizhou Province*

In summary, in karst regions, the relationship between SOC, P, and altitude provides innovative insights. Higher altitudes generally lead to greater SOC content, influenced by cooler temperatures and varying plant species. This diversity enhances organic matter input, crucial for SOC accumulation. A key finding is the critical role of soil moisture, identified as the primary factor influencing SOC in these areas. Moisture supports microbial activity and organic matter decomposition, directly impacting SOC levels. P, especially AP, also plays a significant role in fostering SOC accumulation. It enhances plant growth and microbial efficiency, creating a positive feedback loop: healthy plants increase biomass that decomposes into SOC, and SOC, in turn, improves soil structure and nutrient availability. The study using a random forest method highlights soil moisture, AP, and altitude as top influencers of SOC. This ranking emphasizes the complex interplay of environmental and nutrient factors in karst ecosystems. Overall, these findings deepen understanding of SOC dynamics by linking moisture and phosphorus availability with altitude, offering new perspectives on nutrient cycling and carbon storage in karst forests.

Conclusions

A total of 3 phyla, 4 classes, 26 orders, 49 families, 86 genera and 97 species were recorded based on field investigations of 139 sampling points in forestland in Guizhou

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Province, southwestern China. The plant composition varied with increasing altitude, Both high and low altitudes result in lower vegetation diversity. The SOC content of forestland in Guizhou Province ranged from 3.62 to 148.25 g/kg. The SOC content in Guizhou Province was intermediate in comparison with that in other regions of China. The impact of altitude on forest SOC is significant and that as altitude increases, forest SOC increases. The influence of altitude on forest SOC is primarily attributed to variations in soil moisture, environmental temperature, and soil nutrients, particularly phosphorus. These factors impact species diversity and composition, which in turn determine the quantity and quality of organic carbon input. Additionally, P, especially AP affect the structure and abundance of soil microbial communities, influencing the degradation rate of organic matter and the accumulation of SOC. So, apply phosphorus-rich fertilizers or promote native species that effectively utilize soil phosphorus to boost plant growth and microbial efficiency. Develop altitude-specific strategies, focusing on moisture retention in lower areas and biodiversity maintenance at higher altitudes. Choose plant species suited to specific altitudinal zones to maximize organic matter inputs. Higher altitudes should emphasize species thriving in cooler climates with greater biomass.

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Data availability statement. The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

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APPENDIX

Groups	Main plants		
	Families	**Genus**	**Species**
I<500 m	*Compositae*	*Dendranthema*	*Dendranthema morifolium* (Ramat.) Tzvel.
	Oleaceae	*Osmanthus* *Cornus*	*Osmanthus fragrans* (Thunb.) Lour.
	Fagaceae	*Quercus*	*Quercus fabri* Hance
	Berberidaceae	*Nandina*	*Nandina domestica Thunb.*
	Pittosporaceae	*Pittosporum*	*Pittosporum illicioides* Makino
	Rosaceae	*Eriobotrya*	*Eriobotrya japonica* (Thunb.) Lindl.
		Rosa	*Rosa cymosa* Tratt. var. cymosa
	Anacardiaceae	*Pistacia*	*Pistacia chinensis* Bunge
	Cornaceae	*Cornus*	*Cornus officinalis* Sieb. et Zucc.
	Gramineae	*Miscanthus*	*Miscanthus sinensis* Anderss.
		Neosinocalamus	*Neosinocalamus affinis* (Rendle) Keng
		Phyllostachys	*Phyllostachys heteroclada* Oliver
	Liliaceae	*Rohdea*	*Rohdea japonica* (Thunb.) Roth
	Palmae	*Trachycarpus*	*Trachycarpus fortunei* (Hook.) H. Wendl.
	Taxodiaceae	*Cunninghamia*	*Cunninghamia lanceolata* (Lamb.) Hook.
	Cupressaceae	*Platycladus*	*Platycladus orientalis* (L.) Franco
	Pinales	*Pinus*	*Pinus massoniana* Lamb.
	Dennstaedtiaceae	*Hypolepis*	*Hypolepis punctata* (Thunb.) Mett.
	Gleicheniaceae	*Dicranopteris*	*Dicranopteris dichotoma* (Thunb.) Berhn.
	Nephrolepidaceae	*Nephrolepis*	*Nephrolepis auriculata* (L.) Trimen
	Pteridaceae	*Pteris*	*Pteris cretica* L. var. nervosa (Thunb.) Ching et S. H. Wu

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500≤II<1000	*Compositae*	*Artemisia*	*Artemisia argyi* Levl. et Van.
		Bidens	*Bidens pilosa* L.
		Tanacetum	*Tanacetum vulgare* L.
	Oleaceae	*Ligustrum*	*Ligustrum lucidum* Ait.
		Osmanthus	*Osmanthus fragrans* (Thunb.) Lour.
	Euphorbiaceae	*Vernicia*	*Vernicia fordii* (Hemsl.) Airy Shaw
	Betulaceae	*Betula*	*Betula luminifera* H. Winkl.
	Fagaceae	*Quercus*	*Quercus fabri* Hance
		Cyclobalanopsis	*Cyclobalanopsis glauca* (Thunb.) Oerst.
	Juglandaceae	*Carya*	*Carya cathayensis*
		Pterocarya	*Pterocarya stenoptera*
	Myricaceae	*Myrica*	*Myrica rubra* (Lour.) S. et Zucc.
	Theaceae	*Camellia*	*Camellia oleifera* Abel.
	Myrsinaceae	*Myrsine*	*Myrsine africana* Linn.
	Berberidaceae	*Nandina*	*Nandina domestica* Thunb.
	Lauraceae	*Cinnamomum*	*Cinnamomum bodinieri* Levl.
	Leguminosae	*Indigofera*	*Indigofera tinctoria* Linn
		Robinia	*Robinia pseudoacacia* Linn. Sp. Pl.
	Rosaceae	*Pyracantha*	*Pyracantha fortuneana* (Maxim.) Li
		Rubus	*Rubus biflorus* Buch.-Ham. ex Smith
		Rosa	*Rosa cymosa* Tratt.
	Caprifoliaceae	*Viburnum*	*Viburnum dilatatum* Thunb.
	Meliaceae	*Toona*	*Toona sinensis* (A. Juss.) Roem.
	Rutaceae	*Zanthoxylum*	*Zanthoxylum bungeanum* Maxim.
	Aceraceae	*Acer*	*Acer palmatum* Thunb.
	Coriariaceae	*Coriaria*	*Coriaria nepalensis Wall.*
	Bignoniaceae	*Catalpa*	*Catalpa bungei* C. A. Mey.
	Solanaceae	*Solanum*	*Solanum nigrum* L.
	Urticaceae	*Debregeasia*	*Debregeasia orientalis* C. J. Chen
		Oreocnide	*Oreocnide frutescens* (Thunb.) Miq.
	Moraceae	*Broussonetia*	*Broussonetia papyrifera* (Linn.) L'Hér. ex Vent.
	Gramineae	*Indocalamus*	*Indocalamus tessellatus* (Munro) Keng f.
		Imperata	*Imperata cylindrica (L.) Beauv.*
		Oplismenus	*Oplismenus compositus* (L.) Beauv.
		Neosinocalamus	*Neosinocalamus affinis* (Rendle) Keng
		Panicoideae	*Setaria viridis* (L.) Beauv.
		Phyllostachys	*Phyllostachys heteroclada* Oliver
		Thysanolaena	*Thysanolaena maxima* (Roxb.)Honda
	Palmae	*Trachycarpus*	*Trachycarpus fortunei* (Hook.) H. Wendl.
	Musaceae	*Musa*	*Musa nana*
	Cupressaceae	*Platycladus*	*Platycladus orientalis* (L.) Franco
	Pinales	*Pinus*	*Pinus massoniana* Lamb.
	Taxodiaceae	*Cunninghamia*	*Cunninghamia lanceolata* (Lamb.) Hook.
		Cryptomeria	*Cryptomeria fortunei* Hooibrenk ex Otto et Dietr.
	Dennstaedtiaceae	*Hypolepis*	*Hypolepis punctata* (Thunb.) Mett.
	Gleicheniaceae	*Dicranopteris*	*Dicranopteris dichotoma* (Thunb.) Berhn.
	Nephrolepidaceae	*Nephrolepis*	*Nephrolepis auriculata* (L.) Trimen
	Pteridaceae	*Pteris*	*Pteris cretica* L. var. nervosa (Thunb.) Ching et S. H. Wu
	Sinopteridaceae	*Aleuritopteris*	*Aleuritopteris argentea* (Gmel.) Fee
1000≤III<1500	*Compositae*	*Eupatorium*	*Eupatorium japonicum* Thunb.
		Bidens	*Bidens pilosa* L.
	Oleaceae	*Ligustrum*	*Ligustrum lucidum* Ait.
	Euphorbiaceae	*Sapium*	*Sapium sebiferum* (L.) Roxb.

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		Vernicia	*Vernicia fordii* (Hemsl.) Airy Shaw
	Betulaceae	*Betula*	*Betula luminifera* H. Winkl.
	Fagaceae	*Castanea*	*Castanea mollissima* Bl.
		Cyclobalanopsis	*Cyclobalanopsis glauca* (Thunb.) Oerst.
		Quercus	*Quercus aliena* Bl. var. acuteserrata Maxim. ex Wenz.
			Quercus fabri Hance
	Juglandaceae	*Carya*	*Carya cathayensis*
	Myrtaceae	*Eucalyptus*	*Eucalyptus robusta* Smith
		Myrica	*Myrica rubra* (Lour.) S. et Zucc.
	Nyssaceae	*Camptotheca*	*Camptotheca acuminata* Decne.
	Theaceae	*Camellia*	*Camellia oleifera* Abel.
	Guttiferae	*Hypericum*	*Hypericum monogynum* L.
	Polygonaceae	*Fallopia*	*Fallopia multiflora* (Thunb.) Harald.
		Polygonum	*Polygonum perfoliatum* L.
	Myrsinaceae	*Myrsine*	*Myrsine africana* Linn.
	Lauraceae	*Cinnamomum*	*Cinnamomum camphora* (L.) presl
		Lindera	*Lindera communis* Hemsl.
	Leguminosae	*Campylotropis*	*Campylotropis polyantha* (Franch.) Schindl.
	Rhamnaceae	*Rhamnus*	*Rhamnus heterophylla* Oliv.
	Vitaceae	*Vitis*	*Vitis vinifera L.*
			Vitis heyneana Roem. et Schult. subsp. ficifolia (Bge.) C. L. Li
	Leguminosae	*Albizia*	*Albizia julibrissin* Durazz.
		Caesalpinia	*Caesalpinia decapetala (Roth) Alston*
	Rosaceae	*Amygdalus*	*Amygdalus persica* L.
			Amygdalus davidiana (Carrière) de Vos ex Henry
		Cerasus	*Cerasus pseudocerasus* (Lindl.) G. Don
		Eriobotrya	*Eriobotrya japonica* (Thunb.) Lindl.
		Rosa	*Rosa cymosa* Tratt.
		Rubus	*Rubus biflorus* Buch.-Ham. ex Smith
	Saxifragaceae	*Itea*	*Itea yunnanensis Franch.*
		Prunus	*Prunus salicina* Lindl.
		Pyracantha	*Pyracantha fortuneana* (Maxim.) Li
	Caprifoliaceae	*Viburnum*	*Viburnum foetidum* Wall. var. ceanothoides (C. H. Wright) Hand.-Mazz.
	Caprifoliaceae	*Viburnum*	*Viburnum dilatatum* Thunb.
	Meliaceae	*Toona*	*Toona sinensis (A. Juss.) Roem.*
	Rutaceae	*Zanthoxylum*	*Zanthoxylum armatum* DC.
			Zanthoxylum bungeanum Maxim.
	Anacardiaceae	*Pistacia*	*Pistacia chinensis* Bunge
		Rhus	*Rhus chinensis* Mill.
			Rhus punjabensis Stewart var. sinica (Diels) Rehd. et Wils.
		Toxicodendron	*Toxicodendron vernicifluum (Stokes) F. A. Barkl.*
	Coriariaceae	*Coriaria*	*Coriaria nepalensis* Wall.
	Salicaceae	*Populus*	*Populus adenopoda Maxim.*
	Bignoniaceae	*Catalpa*	*Catalpa bungei* C. A. Mey.
	Araliaceae	*Hedera*	*Hedera nepalensis* K. Koch var. sinensis (Tobl.) Rehd.
		Kalopanax	*Kalopanax septemlobus* (Thunb.) Koidz.
	Urticaceae	*Celtis*	*Celtis sinensis* Pers.
		Debregeasia	*Debregeasia orientalis* C. J. Chen
	Gramineae	*Miscanthus*	*Miscanthus sinensis* Anderss.
		Pennisetum	*Pennisetum alopecuroides* (L.) Spreng.
	Liliaceae	*Smilax*	*Smilax glaucochina*
	Palmae	*Trachycarpus*	*Trachycarpus fortunei* (Hook.) H. Wendl.
	Cupressaceae	*Platycladus*	*Platycladus orientalis* (L.) Franco

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		Sabina	*Sabina chinensis* (L.) Ant.
	Pinaceae	*Pinus*	*Pinus massoniana* Lamb.
	Taxodiaceae	*Cryptomeria*	*Cryptomeria fortunei* Hooibrenk ex Otto et Dietr.
		Cunninghamia	*Cunninghamia lanceolata* (Lamb.) Hook.
	Dennstaedtiaceae	*Hypolepis*	*Hypolepis punctata* (Thunb.) Mett.
	Gleicheniaceae	*Dicranopteris*	*Dicranopteris linearis* (Burm.) Underw.
	Gleicheniaceae	*Dicranopteris*	*Dicranopteris dichotoma* (Thunb.) Berhn.
	Nephrolepidaceae	*Nephrolepis*	*Nephrolepis auriculata* (L.) Trimen
	Pteridaceae	*Pteris*	*Pteris cretica* L. var. nervosa (Thunb.) Ching et S. H. Wu
1500≤IV<2000	*Compositae*	*Artemisia*	*Artemisia sacrorum* Ledeb.
		Bidens	*Bidens pilosa* L.
		Cirsium	*Cirsium japonicum* Fisch. ex DC.
		Kalimeris	*Kalimeris indica* (L.) Sch. -Bip.
	Oleaceae	*Ligustrum*	*Ligustrum lucidum* Ait.
	Ericaceae	*Rhododendron*	*Rhododendron simsii* Planch.
		Vaccinium	*Vaccinium bracteatum* Thunb.
	Betulaceae	*Betula*	*Betula luminifera* H. Winkl.
	Fagaceae	*Castanea*	*Castanea mollissima* Bl.
		Cyclobalanopsis	*Cyclobalanopsis glauca* (Thunb.) Oerst.
		Quercus	*Quercus fabri* Hance
	Geraniaceae	*Geranium*	*Geranium wilfordii* Maxim.
	Juglandaceae	*Carya*	*Carya cathayensis* Sarg
	Myrtaceae	*Syzygium*	*Syzygium buxifolium* Hook. et Arn.
	Thymelaeaceae	*Edgeworthia*	*Edgeworthia chrysantha* Lindl.
	Guttiferae	*Hypericum*	*Hypericum monogynum* L.
			Hypericum patulum Thunb. ex Murray
	Theaceae	*Camellia*	*Camellia sinensis* (L.) O. Ktze.
	Plantaginaceae	*Plantago*	*Plantago depressa* Willd.
	Polygonaceae	*Fallopia*	*Fallopia multiflora* (Thunb.) Harald.
	Berberidaceae	*Mahonia*	*Mahonia fortunei* (Lindl.) Fedde
	Lauraceae	*Cinnamomum*	*Cinnamomum bodinieri* Levl.
	Rosaceae	*Cerasus*	*Cerasus pseudocerasus* (Lindl.) G. Don
		Malus	*Malus halliana* Koehne
		Rosa	*Rosa roxburghii* Tratt.
			Rosa xanthina Lindl.
		Pyracantha	*Pyracantha fortuneana* (Maxim.) Li
		Pyrus	*Pyrus pyrifolia* (Burm. f.) Nakai
	Rutaceae	*Zanthoxylum*	*Zanthoxylum bungeanum* Maxim.
	Aquifoliaceae	*Ilex*	*Ilex crenata* Thunb.
	Coriariaceae	*Coriaria*	*Coriaria nepalensis Wall.*
	Solanaceae	*Lycium*	*Lycium chinense* Mill.
	Gramineae	*Miscanthus*	*Miscanthus sinensis* Anderss.
		Pennisetum	*Pennisetum alopecuroides* (L.) Spreng.
	Cupressaceae	*Platycladus*	*Platycladus orientalis* (L.) Franco
	Pinaceae	*Pinus*	*Pinus massoniana* Lamb.
	Taxodiaceae	*Cunninghamia*	*Cunninghamia lanceolata* (Lamb.) Hook.
		Cryptomeria	*Cryptomeria fortunei Hooibrenk ex Otto et Dietr.*
	Dennstaedtiaceae	*Hypolepis*	*Hypolepis punctata* (Thunb.) Mett.
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	Gleicheniaceae	*Dicranopteris*	*Dicranopteris dichotoma* (Thunb.) Berhn.
	Nephrolepidaceae	*Nephrolepis*	*Nephrolepis auriculata* (L.) Trimen
	Pteridaceae	*Pteris*	*Pteris cretica* L. var. nervosa (Thunb.) Ching et S. H. Wu
2000<V	*Compositae*	*Anaphalis*	*Anaphalis margaritacea* (L.) Benth. et Hook. f.

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		Gerbera	*Gerbera anandria* (L.) Sch.-Bip.
	Fagaceae	*Cyclobalanopsis*	*Cyclobalanopsis glauca* (Thunb.) Oerst.
	Labiatae	*Elsholtzia*	*Elsholtzia ciliata* (Thunb.) Hyland.
	Pinaceae	*Pinus*	*Pinus massoniana* Lamb.
	Thelypteridaceae	*Cyclosorus*	*Cyclosorus interruptus* (Willd.) H. Ito

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