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Soil Carbon, Nitrogen and Phosphorus Fractions and Response to Microorganisms and Mineral Elements in *Zanthoxylum planispinum* 'Dintanensis' Plantations at Different Altitudes

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Abstract: The Carbon (C), nitrogen (N) and phosphorus (P) fractions, mineral element concentrations, microbial density, and biomass in 0–10 and 10–20 cm soil fractions under *Zanthoxylum planispinum* 'dintanensis' plantations, were measured at altitudes of 531, 640, 780, 871, and 1097 m in the mountainous karst areas of Guizhou Province, Southwest China, and the correlations between altitude and the soil variables were analyzed. The results showed that: (1) with the increase in altitude, there was no significant linear change in C fractions, total N, effective N, microorganism density, or mineral element concentration in each soil layer; however, ammonium-N and nitrate-N concentrations gradually decreased, and the P fraction was higher at the highest altitude; (2) soil C, N, and P fractions, concentrations of microorganisms and mineral elements at the same altitude showed a surface aggregation effect; (3) principal component analysis identified the main indicators affecting C, N and P fractions as total calcium, effective calcium, effective iron, total zinc, and bacteria; (4) correlation analysis showed that both total N and C fractions were positively correlated with effective N and P fractions and that mineral element concentrations were more closely correlated with C, N, and (especially) P fractions than with microorganism abundance. Overall, the effect of altitude on C, N, and P fractions showed that the correlation with soluble organic carbon was stronger than particulate organic carbon and easily oxidized carbon, inorganic N was closer correlated than organic N, and organic P was closer correlated than inorganic P. In conclusion, it shows that research focusing on soil N conservation, nutrient stoichiometry balance, and application of mineral-rich element fertilizers is important for *Zanthoxylum planispinum* 'dintanensis' plantation maintenance.

Keywords: altitude; *Zanthoxylum planispinum* 'dintanensis' plantation; soil C, N and P fractions; microorganisms; mineral elements

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1. Introduction

Carbon (C), nitrogen (N) and phosphorus (P) are the most important chemical elements in the soil, and their concentrations affect nutrient cycling and energy flow [1,2]. Mineral elements are essential for plant life and are irreplaceable in growth, development, and metabolism. Microorganisms are the bridge between plants and soil, and their biomass can characterize microbial communities [3,4] and reflect changes in ecosystem function. Mineral elements and microorganisms are also important factors influencing the transformation and transport of soil C, N, and P fractions; therefore, exploring their intrinsic linkages can help reveal the mechanisms driving the accumulation and transformation of soil C, N, and P fractions.

Elevation is a complex environmental factor that can govern soil microbial activity, organic matter dynamics, and nutrient cycling by affecting temperature, moisture, and

slope [5,6], leading to variation in soil C, N, and P with elevation [7,8], which in turn affects their fractional proportions. Kobler et al. [9] showed that the soil C fraction increases with altitude, and Wu et al. [10] found that the C fraction increases and then decreases with increasing altitude. Yang et al. [11] showed that the soil N fraction also increases and then decreases with altitude. De Feudis et al. [12] showed that the P fraction increased with altitude, whereas Che et al. [13] indicated that the N fraction was positively correlated with altitude, but the P fraction showed the opposite trend, indicating that there is no uniformity in the variation pattern of soil C, N, and P fractions in response to altitude. Studies on C, N, and P stoichiometry along altitude gradients have been reported. For example, Zhang et al. [14] found significant differences in the vertical distribution of C, N, and P and their stoichiometric ratios. In contrast, Michael et al. [15] proposed that the concentrations of available soil N, P, C, C:P, and N:P gradually decreased with altitude. In addition, other studies have also shown that soil C, N, and P fractions are closely related to microbial activity and soil enzyme activities [12,16]; furthermore, concentrations of mineral elements can also affect C, N, and P fraction transformations [17]. Taken together, these findings suggest that changes in soil mineral element abundance levels and microbial changes in response to elevation gradients may be important mechanisms affecting C, N, and P fractions, though the mechanisms are not fully understood yet.

Zanthoxylum planispinum 'dintanensis' is a botanical variety of the *Zanthoxylum planispinum* with excellent traits, such as being a drought-tolerant calcicole and lithophyte, and is a pioneer plant for the management of stone desertification and ecosystem restoration. Currently, studies on the effects of altitude on *Z. planispinum* 'dintanensis' have focused on leaf functional traits, ecological studies, and fruit quality [18,19], whereas studies on soil C, N, and P fraction concentrations and their influencing factors are rare. Therefore, we selected sites at different altitudes of a *Z. planispinum* 'dintanensis' plantation to investigate the effect of altitude on soil C, N, and P fractions, microbial abundance, and mineral element concentrations to identify the effects of microorganisms and mineral elements on C, N, and P fractions, to elucidate the nutrient distribution characteristics of Z. planispinum 'dintanensis' plantations in the karst mountains and provide a scientific basis for sustainable management of the forest stands.

2. Materials and Methods

2.1. Overview of the Study Area

The natural vegetation was mainly subtropical evergreen, deciduous broad-leaved mixed forest, whereas the plantation vegetation was *Z. planispinum* 'dintanensis'. Due to the high cost of cultivation in the karst mountains, compound fertilizer (15-15-15 nitrogen-phosphate-potassium fertilizer, in which the nitrogen fertilizer is high nitrogen-sulfur-based compound fertilizer, and phosphate fertilizer is potassium dihydrogen orthophosphate) was applied at a rate of 300–500 g/plant per growing season, a rate also adjusted according to plant growth and climatic conditions. During the study period, management was based on the characteristics of forest age, crown width, and phenology until a relatively stable cultivated *Z. planispinum* 'dintanensis' community was formed [20].

2.2. Experimental Design

Following extensive surveys, we learned that, from the valley floor to the valley shoulder, *Z. planispinum* 'dintanensis' is vertically scattered and grows in the dry tropical valley climate of South Asia and the central subtropical valley climate, with some differences in fertility characteristics and fruit quality traits. Therefore, based on the regional climate and the location in the valley (bottom, slope, and shoulder), as well as the current location of planted *Z. planispinum* 'dintanensis', sample plots were set at 531, 640, 780, 871, and 1097 m elevations, representing south subtropical dry and hot valley climate—valley bottom; south subtropical dry and hot valley climate—buffer zone; south subtropical dry and hot valley climate—valley slope; climate transition zone—valley slope; and central subtropical valley climate—valley shoulder, labeled YD1–YD5, respectively. The forest

age where the samples were collected was approximately 10 years. The sample plots were not set up in an equal series, considering the distribution range of *Z. planispinum* 'dintanensis', the representativeness of sampling, and the avoidance of residential areas. To avoid interference between sampling sites, the distance between two replicates of the same sample was >5 m. The elevation, latitude, longitude, and soil depth of the samples were measured and recorded (Table 1).

Table 1. Sample plots at different altitudes. YD1–YD5 represent sample sites at 531, 640, 780, 871, and 1097 m elevations, respectively.

Sample Plot	Altitude (m)	Longitude and Latitude	pH Value	Slope (°)	Soil Thickness (cm)	Average Tree Height (m)	Average Crown Width (m)	Density (Plants/hm^2)	Vegetation Coverage (%)
YD1	531	105°40′9.9″ E 25°39′57.7″ N	7.05	15	40	4.2	3 × 3	3 × 4	65
YD2	640	105°39′5.6″ E 25°39′46.1″ N	7.86	10	45	4.0	3 × 3.5	4 × 3.5	70
YD3	780	105°38′34.7″ E 25°39′22.4″ N	8.03	10	35	3.7	3 × 3	3.5 × 3	60
YD4	871	105°38′13.9″ E 25°39′17.1″ N	7.89	5	30	3.4	3 × 3.5	3 × 2.8	60
YD5	1097	105°38′15.8″ E 25°38′2.4″ N	6.79	5	40	3.2	3 × 3	3 × 3.2	60

Each sample was sampled using the "S" type five-point sampling method. The soil samples from the 0–10 and 10–20 cm depth profiles were collected separately as mixed samples, put into sterile self-sealing bags, and brought back to the laboratory under low-temperature refrigeration. The soil was then divided into two parts; one was stored for 7 days at 4 °C and used to determine the soil microbial density and biomass, whereas the other was subjected to air-drying and then used to determine the concentrations of the soil C, N, and P fractions and mineral elements.

2.3. Indicators and Measurement Methods

2.3.1. Soil Element Determination

The elements monitored were C, N, P, calcium, magnesium, iron, and zinc; C was determined as total organic C (TOC), and the other elements were determined as total and available concentrations. TOC was determined by the potassium dichromate oxidation-external heating method, total N (TN) was determined by the modified Kjeldahl method, total P (TP) was determined by the perchloric acid-sulfuric acid digestion-molybdenum antimony UV/visible spectrophotometric method, and total calcium (Tca), total magnesium (TMg), total iron (Tfe), and total zinc (TZn) were determined by acid digestion with nitric acid-perchloric acid mixture-inductively coupled plasma–optical emission spectroscopy (ICP-OES) [21]. Available N (AN) concentration was determined by the alkali diffusion method, and available (fast-acting) P (AP) was determined by the ammonium fluoride-hydrochloric acid leaching-molybdenum antimony UV/visible spectrophotometric method. The soil's available calcium (ACa), available magnesium (AMg), available iron (AFe), and available zinc (AZn) concentrations were extracted with AB-DTPA and determined using ICP-OES [21].

2.3.2. Determination of Soil C, N, and P Fractions

The fractions included easily oxidizable carbon (EOC), dissolved organic carbon (DOC), particulate organic carbon (POC), ammonium nitrogen (NH_4^+-N), nitrate nitrogen (NO_3^--N), active phosphorus (OP), moderately active phosphorus (OP1), phosphorus in agglomerates (SP), calcium phosphorus (Ca-P), and closed storage phosphorus (O-P). EOC was determined by the K_2SO_4 oxidation-colorimetric method [22]. DOC by the UP water shaking extraction-TOC [23], POC by the potassium dichromate oxidation-external heating method [24], NH_4^+-N, and NO_3^--N were determined by the indigo colorimetric method

and phenol disulfonic acid colorimetric method, respectively [21]. The soil P fraction was determined by the Hedley continuous leaching method [25,26].

2.3.3. Microbial Soil Concentration and Biomass Determination

Soil bacterial, fungal, and actinomycete concentrations were determined using suspension spreads on beef peptone medium, potato dextrose agar medium, and Gao's No. 1 agar medium, respectively, and bacteria and actinomycetes were counted by dilution plate counting method, and fungi were counted by the inverted dish method. After the soil samples were sterilized by chloroform fumigation, the microbial biomass of carbon(MBC) and microbial biomass of nitrogen(MBN) were determined by the potassium dichromate sulfate external heating method and the Kjeldahl nitrogen method, respectively. The microbial biomass of phosphorus(MBP) was determined by the molybdenum blue colorimetric method [27].

2.4. Data Processing and Statistical Analysis

Microsoft Excel 2010 software was used to organize and analyze the data. Two-way analysis of variance (AVOVA) and Duncan's multiple range test were used to test the significance of differences in concentration of C, N, and P fractions, microorganisms, and mineral elements from samples taken at different altitudes and soil depths. Principal component analysis (PCA) was used to identify the mineral elements and microbial concentrations affecting soil C, N, and P fractions. Pearson's correlation analysis was used to test the correlation of different soil indicators. SPSS 20.0 (IBM, Armonk, NY, USA) and Origin 8.6 software were used to complete the analyses and construct the graphics.

3. Results

3.1. Characteristics of Soil C, N, and P Fractions at Different Altitudes

The patterns of variation in soil C, N, and P fractions in response to increasing altitude differed, with the C, N, and P fractions showing a "surface aggregation" distribution effect. In general, the patterns of variation of C fractions with elevation were weak, and only DOC increased with elevation (Figure 1); TN and AN showed no significant variation pattern in response to increasing elevation, whereas NH_4^+-N and NO_3^--N concentrations gradually decreased and the P fraction concentration was highest in YD5 (Figure 1). Altitude, soil depth, and the [altitude × soil depth] interaction had the greatest effect on the soil P fraction, followed by the N fraction, had the least effect on the C fraction, and significantly ($p < 0.05$) or highly significantly ($p < 0.01$) affected the DOC, POC, N fraction and P fraction (except Ca-P) concentrations (Table 2).

Table 2. ANOVA test results for the effects of altitude and soil depth on soil carbon, nitrogen, and phosphorus fractions. TOC: Total organic carbon; POC: Particulate organic carbon; DOC: Dissolved organic carbon; EOC: Easily oxidized carbon; TN: Total nitrogen; AN: Available nitrogen; NH_4^+-N: Ammonium nitrogen; NO_3^--N: Nitrate nitrogen; TP: Total phosphorus; AP: Available phosphorus; O-P: Closed storage phosphorus; OP1: Moderately active phosphorus; OP: Active phosphorus; Ca-P: Calcium phosphorus; SP: Phosphorus in agglomerates.

Factor	TOC		POC		DOC		EOC		TN		AN		NH_4^+-N		NO_3^--N	
	F	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Altitude	0.17	0.95	3.05	0.07	20.67	<0.01	1.73	0.22	0.17	0.95	3.05	0.07	20.67	<0.01	1.73	0.22
Soil depth	5.30	<0.05	43.12	<0.01	1.52	0.25	3.68	0.08	5.30	<0.05	43.12	<0.01	1.52	0.25	3.68	0.08
Altitude × Soil depth	0.92	0.49	2.60	0.10	1.88	0.19	0.95	0.47	0.92	0.49	2.60	0.10	1.88	0.19	0.95	0.47
Factor	TP		AP		O-P		OP1		OP		Ca-P		SP			
	F	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*		
Altitude	41.23	<0.01	26.55	<0.01	4.35	<0.05	18.10	<0.01	38.513	<0.01	2.64	0.097	34.40	<0.01		
Soil depth	40.28	<0.01	40.46	<0.01	0.99	0.34	19.27	<0.01	43.196	<0.01	5.68	0.038	15.11	<0.01		
Altitude × Soil depth	6.25	<0.01	10.47	<0.01	0.29	0.88	4.78	<0.05	16.433	<0.01	1.28	0.342	3.20	0.062		

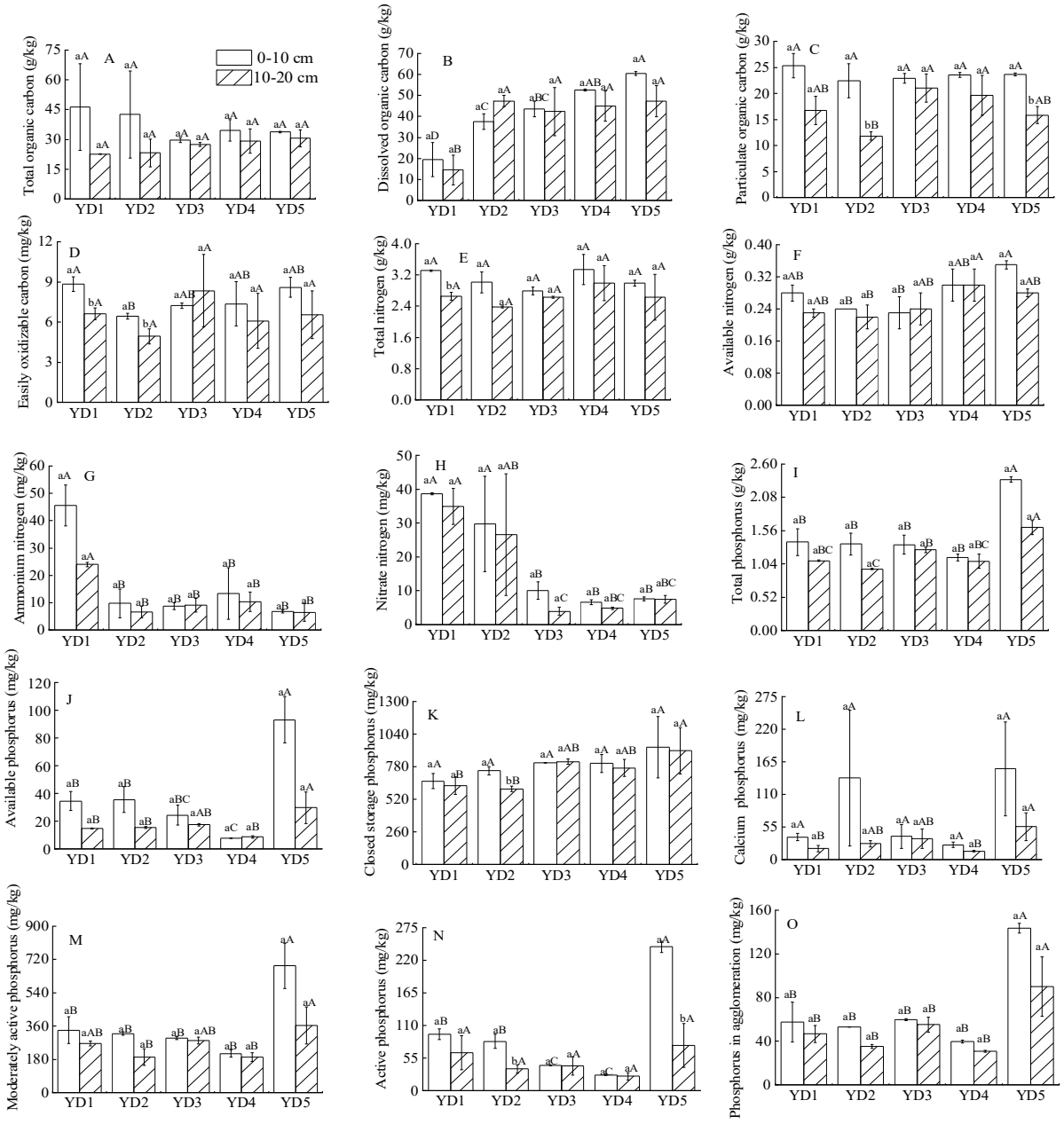

Figure 1. Effect of altitude on the concentration of total organic carbon (**A**), dissolved organic carbon (**B**), particulate organic carbon (**C**), easily oxidizable carbon (**D**), total nitrogen (**E**), available nitrogen (**F**), ammonium nitrogen (**G**), nitrate nitrogen (**H**), total phosphorus (**I**), available phosphorus (**J**), closed storage phosphorus (**K**), calcium phosphorus (**L**), moderately active phosphorus (**M**), active phosphorus (**N**), phosphorus in agglomerates (**O**), of soils in different soil depths of the *Zanthoxylum planispinum* 'dintanensis' plantation. Different uppercase letters indicate significant differences among different altitudes at the same soil depth ($p < 0.05$), whereas different lowercase letters indicate significant differences between different soil depths at the same altitude ($p < 0.05$). Data points represent mean ± standard deviation.

3.2. Soil Microbial Concentration and Biomass at Different Altitudes

The response of soil microbial concentration to increasing altitude was greater than that of microbial biomass. However, the differences in microbial concentration and biomass between different soil depths were not significant. At the same soil depth, bacterial concen-

tration gradually decreased with increasing elevation, whereas the concentrations of fungi and actinomycetes first increased and then decreased as altitude increased, whereas MBP decreased then increased, and there was no significant variation pattern of MBC and MBN (Figure 2). Altitude, soil depth, and [altitude × soil depth] interaction had less influence on soil microbial concentration and biomass, with altitude having highly significant and significant effects on bacteria and MBP, respectively; soil depth had a significant effect on fungus abundance, but the [altitude × soil depth] interaction had no significant effect on microbial concentration or biomass ($p > 0.05$) (Table 3).

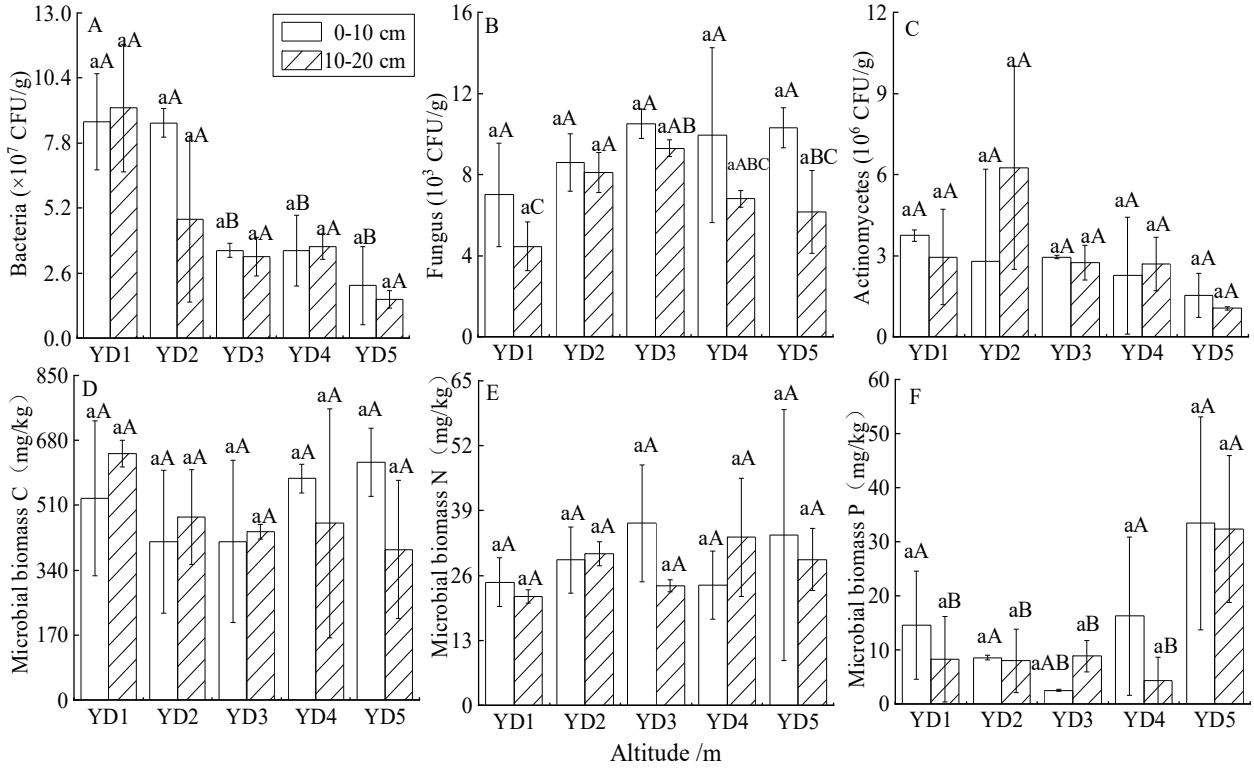

Figure 2. Effect of altitude on soil bacteria (**A**), fungi (**B**), actinomycetes (**C**), microbial biomass carbon (**D**), microbial biomass nitrogen (**E**), microbial biomass phosphorus (**F**) at different soil depths of the *Zanthoxylum planispinum* 'dintanensis' plantation. Different uppercase letters indicate significant differences among different altitudes in the same soil depth ($p < 0.05$), whereas different lowercase letters indicate significant differences between different soil depths at the same altitude ($p < 0.05$). Data points represent mean ± standard deviation.

Table 3. ANOVA test results for the effects of altitude and soil depth on soil microbial concentration and biomass. BAC: Bacteria; FUN: Fungi; ACT: Actinomycetes; MBC: Microbial biomass carbon; MBN: Microbial biomass nitrogen; MBP: Microbial biomass phosphorus.

Factor	BAC		FUN		ACT		MBC		MBN		MBP	
	F	***P***	***F***	***P***	***F***	***P***	***F***	***P***	***F***	***P***	***F***	***P***
Altitude	12.20	<0.01	2.54	0.11	1.58	0.25	0.59	0.68	0.39	0.81	4.73	<0.05
Soil depth	1.16	0.31	7.50	<0.05	0.33	0.28	0.58	0.72	0.16	0.70	0.37	0.56
Altitude × Soil depth	01.15	0.39	0.61	0.67	0.84	0.53	0.75	0.58	0.62	0.66	0.47	0.76

3.3. Characteristics of Soil Mineral Elements at Different Altitudes

The variation pattern of mineral element concentrations in response to altitude was strong, but there was no significant difference in mineral element concentration at different soil depths. Overall, the concentrations of TCa, ACa, TMg, and AMg increased and then

decreased with increasing altitude, whereas the concentrations of TFe and TZn had no significant variation pattern with altitude, but the concentrations of AFe and AZn were highest in YD5 (Figure 3). Altitude had the strongest effect on mineral element concentration, except for TFe, having a highly significant or significant effect on the concentration of different elements; soil depth and [soil depth × altitude] had a highly significant and significant effect, respectively, on AZn (Table 4).

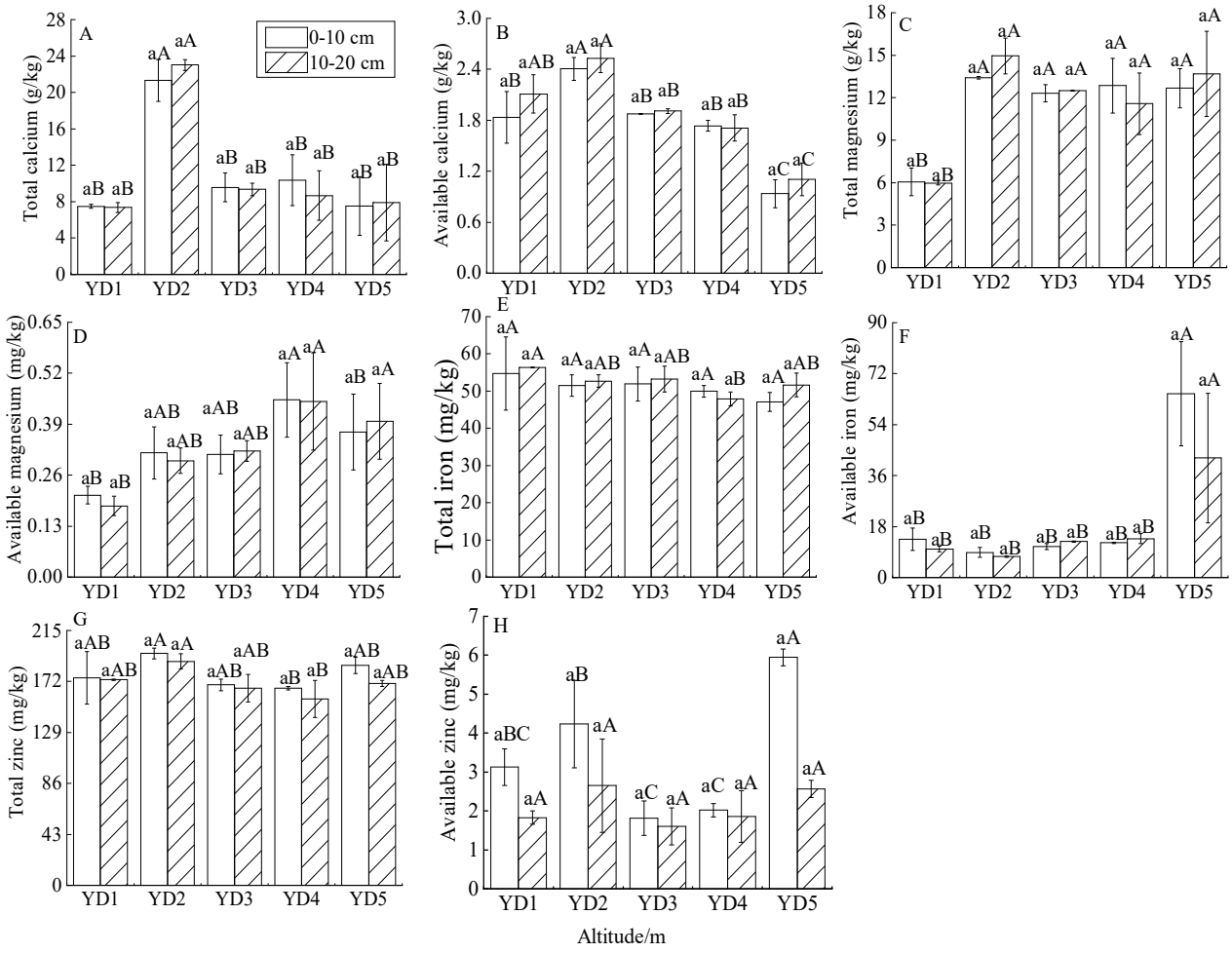

Figure 3. Effect of altitude on the total calcium (**A**), available calcium (**B**), total magnesium (**C**), available magnesium (**D**), total iron (**E**), available iron (**F**), total zinc (**G**), available zinc (**H**) in soil at different soil depths of the *Zanthoxylum planispinum* 'dintanensis' plantation. Different uppercase letters indicate significant differences among different altitudes at the same soil depth ($p < 0.05$), whereas different lowercase letters indicate significant differences between different soil depths at the same altitude ($p < 0.05$). Data points represent mean ± standard deviation.

Table 4. ANOVA test results for the effects of altitude and soil depths on soil mineral element concentrations. TCa: Total calcium; ACa: Available calcium; TMg: Total magnesium; AMg: Available magnesium; TFe: Total iron; AFe: Available iron; TZn: Total zinc; AZn: Available zinc.

Factor	TCa		ACa		TMg		AMg		TFe		AFe		TZn		AZn	
	F	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Altitude	151.99	<0.01	38.84	<0.01	18.70	<0.01	6.84	<0.01	1.76	0.21	16.67	<0.01	5.32	<0.05	11.57	<0.01
Soil depth	0.00	1.00	2.38	0.15	0.17	0.69	0.01	0.93	0.54	0.48	1.35	0.27	2.44	0.15	22.30	<0.01
Altitude × Soil depth	0.29	0.88	0.48	0.75	0.64	0.71	0.09	0.98	0.33	0.85	1.18	0.38	0.29	0.88	4.38	<0.05

3.4. Relationship between Soil C, N, and P Fractions and Microbial Concentration and Mineral Element Concentrations

3.4.1. Principal Component Analysis of Mineral Element and Microbial Concentrations

Based on the principle of loadings >1 and cumulative contribution >80%, four principal components were identified, and factors with loadings >0.7 (determined based on the loadings of different indicators) were extracted to further analyze their response characteristics on soil C, N, and P fractions. TCa, ACa, AFe, TZn, and BAC were identified as having strong effects on C, N, and P fractions (Table 5).

Table 5. Principal component analysis of mineral elements and microorganisms. Note: TCa: Total calcium; ACa: Available calcium; TMg: Total magnesium; AMg: Available magnesium; TFe: Total iron; AFe: Available iron; TZn: Total manganese, AZn: Available zinc, BAC: Bacteria; FUN: Fungi; ACT: Actinomycetes.

Factor	PC 1	PC 2	PC 3	PC 4
TCa	0.215	0.930	−0.200	−0.112
ACa	0.773	0.497	−0.247	−0.089
TMg	−0.505	0.603	−0.495	−0.197
AMg	−0.595	0.116	−0.659	0.093
TFe	0.655	−0.010	0.286	−0.058
AFe	−0.803	−0.163	0.486	0.105
TZn	0.020	0.768	0.564	0.091
AZn	−0.512	0.398	0.629	0.157
BAC	0.783	0.160	0.267	0.338
FUN	−0.439	0.376	−0.161	0.645
ACT	0.430	−0.249	−0.404	0.623
Eigenvalue	2.875	2.782	2.322	1.199
Contribution rate %	26.135	25.294	21.114	10.903
Cumulative contribution rate %	26.135	51.429	75.543	83.446

3.4.2. Correlation Analysis among Soil C, N, and P Fractions with Mineral Element and Microbial Concentrations

Soil TP was highly significantly and positively correlated with the P fraction, indicating that the concentration of the P fraction depends to some extent on the storage of TP. There were some correlations among C, N, and P fractions, with soil TN being highly significantly and positively correlated with TOC, POC, and EOC. DOC was significantly and positively and highly significantly and negatively correlated with AN, NH_4^+-N, and NO_3^--N, indicating antagonistic or synergistic effects between C and N fractions. AN and AFe showed the strongest correlation with the P fraction, followed by the N fraction, indicating that AFe tended to influence the conversion and accumulation of the P fraction. ACa showed significant and highly significant negative correlations with AN and SP, respectively. TCa showed a significant negative correlation with OP, and TZn showed no significant correlation with the C, N, or P fractions. BAC exhibited a significant negative correlation with DOC, indicating that BAC concentration had a certain inhibitory effect on soluble organic C synthesis and accumulation. In summary, the concentrations of both mineral elements and microbes influenced soil C, N, and P fractions, with mineral element concentration having a greater influence and the concentration of the available fraction having a greater effect than that of the total fraction (Table 6).

Table 6. Correlation analysis among soil C, N, and P fractions and concentrations of mineral elements and microbes.

Indicators	TOC	POC	DOC	EOC	MBC	TN	AN	NH_4^+-N	NO_3^--N	MBN	TP	AP	O-P	OP1	OP	SP	Ca-P	MBP	TCa	ACa	AFe	TZn
POC	0.651 **	1																				
DOC	−0.024	0.035	1																			
EOC	0.407	0.588 **	0.099	1																		
MBC	−0.190	0.145	−0.027	0.272	1																	
TN	0.629 **	0.739 **	0.036	0.590 **	0.315	1																
AN	0.239	0.349	0.450 *	0.513 *	0.167	0.498 *	1															
NH_4^+-N	0.357	0.349	−0.725 **	0.372	0.295	0.485 *	0.022	1														
NO_3^--N	0.333	−0.045	−0.723 **	−0.089	0.133	0.061	−0.421	0.639 **	1													
MBN	0.008	−0.026	0.281	−0.024	−0.196	0.015	−0.062	−0.203	−0.143	1												
TP	0.210	0.370−	0.384	0.479 *	0.145	0.226	0.610 **	−0.100	−0.223	0.214	1											
AP	0.170	0.319	0.312	0.369	0.275	0.142	0.468 *	−0.059	−0.060	0.131	0.905 **	1										
O-P	0.099	0.322	0.594 **	0.461 *	0.022	0.320	0.487 *	−0.319	−0.613 **	0.500 *	0.640 **	0.376	1									
OP1	0.154	0.339	0.283	0.450 *	0.278	0.191	0.524 *	−0.034	−0.131	0.060	0.947 **	0.965 **	0.460 *	1								
OP	0.233	0.280	0.210	0.396	0.180	0.119	0.539 *	0.004	0.033	0.135	0.891 **	0.915 **	0.325	0.890 **	1							
SP	0.038	0.183	0.337	0.341	0.106	−0.032	0.527 *	−0.170	−0.226	0.145	0.939 **	0.870 **	0.493 *	0.897 **	0.901 **	1						
Ca-P	0.472 *	0.336	0.266	0.264	−0.144	0.251	0.253	−0.154	0.102	0.419	0.698 **	0.600 **	0.509 *	0.588 **	0.667 **	0.559 *	1					
MBP	0.127	0.015	0.293	0.085	−0.047	−0.107	0.502 *	−0.188	−0.194	−0.295	0.580 **	0.559 *	0.134	0.593 **	0.616 **	0.705 **	0.213	1				
TCa	−0.106	0.264	0.055	−0.192	−0.207	−0.030	−0.306	−0.162	−0.400	0.257	−0.338	−0.347	0.085	−0.349	−0.453 *	−0.375	−0.298	−0.325	1			
ACa	−0.240	−0.086	−0.187	−0.291	−0.249	−0.245	−0.557 **	−0.089	−0.030	0.279	−0.430	−0.337	−0.108	−0.390	−0.402	−0.463 *	−0.169	−0.389	0.700 **	1		
AFe	0.065	0.075	0.344	0.131	0.185	0.099	0.610 **	−0.122	−0.267	−0.338	0.458 *	0.419	0.099	0.474 *	0.431	0.563 **	0.039	0.646 **	−0.424	−0.839 **	1	
TZn	−0.100	0.383	0.119	0.133	0.122	0.205	0.130	0.050	−0.437	0.078	0.200	0.173	0.227	0.252	0.063	0.212	−0.131	0.227	0.568 **	0.203	0.168	1
BAC	−0.347	−0.153	−0.456 *	−0.193	0.156	−0.044	−0.440	0.297	0.314	0.080	−0.404	−0.249	−0.418	−0.305	−0.259	−0.344	−0.331	−0.278	0.238	0.567 **	−0.493 *	0.268

Note: * indicates significant correlation ($p < 0.05$), ** indicates a very significant correlation ($p < 0.01$).

4. Discussion

4.1. Changes in Soil C, N, and P Fractions at Different Altitudes

There was no significant difference in soil TOC concentrations at sites at different altitudes in the research described in this paper. This finding differs from the results of Yu et al. [28], who concluded that TOC concentration was significantly higher at high-altitude sites than at low-altitude sites. The reason for this discrepancy may be that TOC concentration is affected by temperature, microorganisms, etc., but also by the type, quantity, and quality of apoplankton [29–31]; meanwhile, plantation forests grow faster at lower altitudes, with more soil nutrients being taken up and utilized by plants at lower altitudes which correspond to higher *Z. planispinum* 'dintanensis' vegetation densities. DOC is more sensitive to elevation changes than POC and EOC for the following reasons. First, DOC is a direct source of TOC used by microorganisms and is easily transported, decomposed, and mineralized in the soil [32]. Second, DOC is readily soluble in the soil solution and hence lost. The higher the percentage of TOC, the lower the TOC stability and accumulation potential [33,34]. Overall, the higher concentration of POC and EOC in the topsoil in this study indicates that the topsoil TOC stability is poorer, and the TOC accumulation capacity is lower. The reasons for these results are that topsoil is richer in nutrients than deeper soils, with higher microbial concentration and activity, and hence with greater decomposition and mineralization of soil TOC, while topsoil is also more readily disturbed by humans and less stable, traits which are not conducive to TOC accumulation.

The changes in soil TN concentration with increasing altitude in this area were insignificant, indicating that altitude is not a main factor controlling TN concentration due to the abundance of soil N sources, such as biological N fixation, N fertilizer application, and the decomposition of apoplankton, etc. Many factors jointly regulate the migration and transformation of N. Altitude has a highly significant effect on soil AN, NH_4^+-N and NO_3^--N concentrations, specifically NH_4^+-N >NO_3^--N > AN (Table 2), indicating that elevation tended to affect soil inorganic N. Because inorganic N is an N source that can be directly absorbed and utilized by plants, different plant species have different abilities to absorb and utilize N. Elevation regulates soil inorganic N by directly affecting environmental factors and limiting vegetation distribution and growth conditions. NH_4^+-N and NO_3^--N are the main forms of inorganic N in the soil. NH_4^+-N and NO_3^--N concentrations decrease with increasing altitude in the same soil layer due to lower temperatures at high altitudes, which limits the activity of mineralization- and nitrification-related microorganisms, thus inhibiting these transformation processes. At the same time, soil moisture content at a certain altitude may promote microbial denitrification activity [35] so that denitrification is enhanced and gaseous N losses are elevated, leading to a decrease in NH_4^+-N and NO_3^--N as a percentage of the N fraction.

Natural terrestrial ecosystem soils are generally P limited, with soil P-based constraints most prominent in the tropics [2,36]. TP content was highest in YD5, suggesting that soils at higher elevations in this region are relatively less likely to be P limited. The effect of altitude on P fraction concentrations revealed an order of OP > SP > AP > OP1 > O-P > Ca-P (Table 2), indicating a greater effect of altitude on organic P. The reason for this may be that altitude is an important factor affecting temperature, microbial concentration, and activity, with organic P decomposition and mineralization being more strongly influenced by temperature and microorganisms than inorganic P, resulting in a more sensitive response of organic P to altitude. However, the effects of temperature and microorganisms on organic and inorganic P were not measured in the current paper but need to be studied in depth in the future. The P fraction concentration was highest in YD5; where the elevation increased, the temperature and microbial concentration and activity decreased, the degree of soil weathering and mineralization of native mineral P and organic P decreased [37,38], Fe, aluminum (Al) oxide adsorption fixation of inorganic P decreased [39]. The pH of YD5 was the lowest (Table 1), with low pH favoring the increase in soil P concentration in the easily decomposed state [37]. It was also found that soil C, N, and P concentrations showed a surface aggregation effect due to superior conditions of apoplastic topsoil biomass, root

secretion, and temperature, with higher microbial activity [40] and faster decomposition of apoplastic material, releasing more nutrients.

4.2. Changes in Soil Microorganisms and Nutrients at Different Altitudes

In general, the concentration of bacteria, fungi, and actinomycetes in this area are relatively low at high altitude, a finding consistent with the results of Singh et al. [41], as a result of the decrease in temperature and increase in precipitation with increasing altitude, which limits the decomposition of organic matter [42,43]. In addition, the slope of land may increase at high altitude, causing increased erosion to carry away more nutrients, resulting in lower soil nutrient concentrations and unfavorable microbial growth and multiplication. Elevation had no significant effect on MBC or MBN (Figure 2, Table 3). The highest MBP concentration was found at site YD5, consistent with TP concentration. The relatively low MBP content at low elevation is presumed to be due to the following reasons: the population is more clustered at moderate elevations, which disturbs the soil more, affecting the soil conditions at the same time; coupled with the high temperature, which favors plant growth, the competition between vegetation and microorganisms is enhanced, thus inhibiting microbial activity [44].

The soil calcium concentration increases first and then decreases with increasing altitude, reaching its highest level at YD2, which is significantly higher than the concentration at other sample sites because of the high precipitation at high altitude and the enhanced Ca leaching, which causes the soil Ca concentration to decrease. Furthermore, the high-altitude area is also the transition area from carbonate to sand shale, and the Ca concentration in the parent rock is lower. Neither soil TFe nor TZn differed significantly with increasing altitude, whereas AFe and AZn concentrations are highest at YD5, which may be related to the soil acid-base background and physical properties. The karst area has an alkaline soil, and soil Fe and Zn ions react with hydroxide (OH^-) to produce sediment to be fixed, and soil pH is lowest at YD5 (Table 1). The OH^- concentration is relatively low, producing sediment to be fixed at moderate and low altitudes; this is the main farming area, and the anthropogenic tillage causes a decrease in soil capacity and an increase in pore space, which leads to greater soil Fe and Zn leaching.

4.3. Relationships between Soil C, N, and P Fractions and Concentrations of Microorganisms and Mineral Elements

The correlation between soil TC and POC was greater than that of other active organic C fractions, indicating that POC is the fraction most sensitive to changes in soil TOC and most likely a sensitive indicator of TOC dynamics. TN showed a highly significant positive correlation with both POC and EOC and a stronger positive correlation with AN and P fractions because microorganisms are more likely to decompose soils with high N content [45], suggesting that the effect of N on C and P fractions is mainly mediated by microorganisms and that improving soil N conditions can promote C and P accumulation. Therefore, the management of *Z. planispinum* 'dintanensis' plantations should pay attention to protecting soil N and the apoplastic surface layer. If necessary, measures such as incorporating N fertilizer into the soil tillage layer or applying fertilizer during the growth period should be undertaken. There is a strong positive correlation between the concentration of soil P fractions, indicating that the P fractions are closely related and jointly influence the turnover and function of soil P. The strong positive correlations between concentrations of mineral elements and P fractions indicate that mineral elements respond more strongly to P fractions than to C or N fractions. It is assumed that mineral elements can sensitively characterize P fraction dynamics. The reason is that soil P concentration is more stable and is mainly mediated by the soil-forming parent material and rock weathering, which is the material basis of soil formation and the initial source of mineral elements [46], and changes in concentrations of mineral elements can influence the distribution of soil P fractions. Therefore, during *Z. planispinum* 'dintanensis' cultivation, mineral-rich nutrient

fertilizers can be applied to promote P accumulation, improve soil fertility, and alleviate soil P limitation.

MBN content can characterize soil N effectiveness, and the greater the MBN, the higher the soil N availability [47]. MBN in this area is positively correlated with DOC and negatively correlated with NO_3^--N concentration, indicating that high N availability can promote soil C accumulation and discourage N accumulation. Therefore, the cultivation process of *Z. planispinum* 'dintanensis' plantations needs to regulate the soil nutrient balance. However, the research described in this study did not quantify the soil nutrient stoichiometric balance, especially the relationship between C and N element stoichiometric balance, which still needs to be explored in depth in the future. Bing et al. [48] concluded that MBP plays an important role in soil P cycling and plant P supply, and MBP turnover can compensate for P in soil solution when P is scarce and can promote plant uptake and utilization of P. Lin et al. [49] found that MBN may indirectly affect P concentration through the synthesis of acid phosphatase, but the correlation in the current study between MBN and P components was low, and only O-P was positively correlated with MBN, which was different from the view supporting the concept that MBN may indirectly regulate P fraction conversion through the synthesis of acid phosphatase. However, the present study did not measure soil acid phosphatase activity, which makes it difficult to support this view. Therefore, future studies on the response of microbial biomass to acid phosphatase synthesis need to be further explored.

5. Conclusions

Temperature and plant changes along the altitude gradient cause changes in concentrations of soil C, N, and P, their fractions, and microbial populations. At the same soil depth, the concentration of C and N fractions, microorganisms, and mineral elements are not significant, and the concentration of P fractions is highest in YD5; the concentration of C, N, and P fractions, microorganisms, and mineral elements at the same altitude. Soil TCa, ACa, TFe, TZn, and BAC are important factors affecting the transformation and movement of the C, N, and P fractions in the soil. The relationship between concentrations of mineral elements and C, N, and P fractions is stronger than that of microorganisms, indicating that, compared with microorganisms, mineral elements are more sensitive to soil nutrient changes, especially the content of P fractions, and the concentration of the available fraction is stronger than that of the total fraction.

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References

1. Bertolet, B.L.; Corman, J.R.; Casson, N.J.; Sebestyen, S.D.; Kolka, R.K.; Stanley, E.H. Influence of soil temperature and moisture on the dissolved carbon, nitrogen, and phosphorus in organic matter entering lake ecosystems. *Biogeochemistry* **2018**, *139*, 293–305. [CrossRef]
2. Hou, E.; Luo, Y.; Kuang, Y.; Chen, C.; Lu, X.; Jiang, L.; Luo, X.; Wen, D. Global meta-analysis shows pervasive phosphorus limitation of aboveground plant production in terrestrial ecosystems. *Nat. Commun.* **2020**, *11*, 637. [CrossRef]
3. He, Z.L.; Yang, X.E.; Baligar, V.C.; Calvert, D.V. Microbiological and biochemical indexing systems for assessing quality of acid soils. *Adv. Agron.* **2003**, *78*, 89–138.

4. Leff, J.W.; Jones, S.E.; Prober, S.M.; Barberán, A.; Borer, E.T.; Firn, J.L.; Harpole, W.S.; Hobbie, S.E.; Hofmockel, K.S.; Knops, J.M.H.; et al. Consistent responses of soil microbial communities to elevated nutrient inputs in grasslands across the globe. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 10967–10972. [CrossRef] [PubMed]
5. Chang, E.H.; Chen, T.H.; Tian, G.L.; Chiu, C.Y. The effect of altitudinal gradient on soil microbial community activity and structure in no so bamboo plantations. *Appl. Soil Ecol.* **2016**, *98*, 213–220. [CrossRef]
6. He, X.; Hou, E.; Liu, Y.; Wen, D. Altitudinal patterns and controls of plants and soil nutrient concentration and stoichiometry in subtropical China. *Sci. Rep.* **2016**, *6*, 24261. [CrossRef]
7. Chen, L.F.; He, Z.B.; Du, J.; Yang, J.J.; Zhu, X. Patterns and environmental controls of soil organic carbon and total nitrogen in alpine ecosystems of northwestern China. *Catena* **2016**, *137*, 37–43. [CrossRef]
8. Qin, Y.; Feng, Q.; Holden, M.N.; Cao, J. Variation in soil organic carbon by slope aspect in the middle of the Qilian Mountains in the upper Heihe River Basin, China. *Catena* **2016**, *147*, 308–314. [CrossRef]
9. Kobler, J.; Zehetgruber, B.; Dirnböck, T.; Jandl, R.; Mirtl, M.; Schindlbacher, A. Effects of aspect and altitude on carbon cycling processes in a temperate mountain forest catchment. *Landscape Ecol.* **2019**, *34*, 325–340. [CrossRef]
10. Wu, Y.; Zhao, P.P.; Lin, K.S.; Zhou, J.C.; Lv, M.K.; Zhang, Q.F.; Zheng, W.; Cheng, L.; Xu, J.G.; Chen, Y.M. Elevation gradient characteristics and impact factors of soil carbon fractions in the *Pinus taiwanensis* Hayata forests of Daiyun Mountain. *Acta Ecol. Sin.* **2020**, *40*, 5761–5770.
11. Yang, Q.F.; Xiong, Y.; Yu, Z.P.; Liu, Z.; Liu, X.Y.; Xi, D. Characteristics of soil active nitrogen fractions in evergreen broad-leaved forests at different altitudes in Guanhan mountain of eastern China. *J. Cent. South Univ. For. Technol.* **2021**, *41*, 138–147.
12. De Feudis, M.; Gardelli, V.; Massaccesi, L.; Willbold, R.B.; Cocco, S.; Corti, S.; Agnelli, A. Effect of beech (*Fagus sylvatica* L.) rhizosphere on phosphorus availability in soils at different altitudes (Central Italy). *Geoderma* **2016**, *276*, 53–63. [CrossRef]
13. Che, M.X.; Wu, Q.; Fang, H.; Kang, C.F.; Lü, C.; Xu, M.J.; Gong, Y.B. Effects of elevation and slope aspect on soil nitrogen and phosphorus distribution of western Sichuan Plateau shrub meadow. *Chin. J. Appl. Environ. Biol.* **2021**, *27*, 1163–1169.
14. Zhang, G.S.; Deng, H.J.; Du, K.; Lin, Y.M. Soil stoichiometry characteristics at different elevation gradient of a mountain in an area with high-frequency debris flow: A case study in Xiaojiang Watershed, Yunnan. *Acta Ecol. Sin.* **2016**, *36*, 675–687.
15. Michael, M.; Yvonne, O.; Udo, S.; Jurgen, B.; Thomas, S. Himalayan treeline soil and foliar C: N:P stoichiometry indicate nutrient shortage with elevation. *Geoderma* **2017**, *291*, 21–32.
16. Soussana, J.F.; Lemaire, G. Coupling carbon and nitrogen cycles for environmentally sustainable intensification of grasslands and crop-livestock systems. *Agr. Ecosyst. Environ.* **2014**, *190*, 9–17. [CrossRef]
17. Mao, Q.G.; Lu, X.K.; Cheng, H.; Mo, J.M. Responses of terrestrial plant diversity to elevated mineral element inputs. *Acta Ecol. Sin.* **2015**, *35*, 5884–5897.
18. Yanghua, Y.; Wei, Z.; Xinping, Z.; Bin, Y. Stoichiometric characteristics in Z *anthoxylum planispinum* var. 'dintanensis' plantation of different ages. *Agron. J.* **2020**, *113*, 685–695. [CrossRef]
19. Song, Y.P.; Yu, Y.H.; Li, Y.T. Leaf Function Traits and relationships with Soil Properties of *Zanthoxylum planispinum* 'dintanensis'in Plantations of Different Ages. *Agronomy* **2022**, *12*, 1891. [CrossRef]
20. Zou, J.; Yu, L.F.; Huang, Z.S. Variation of leaf carbon isotope in plants in different lithological habitats in a karst area. *Forest* **2019**, *10*, 356. [CrossRef]
21. Bao, S.D. *Soil Agricultural Analysis*, 3rd ed.; China Agricultural Publishing House: Beijing, China, 2000; pp. 30–177.
22. Zhang, J.H.; Ding, W.X.; Meng, L. Spatial variability of soil labile organic carbon in the tropical rubber plantations of Hainan province, China. *Ecol. Environ. Sci.* **2010**, *19*, 2563–2567.
23. Han, L.; Zhang, Y.L.; Jing, S.; Wang, J.; Wei, Y.Y.; Cui, N.; Wei, W. Effects of Different Irrigation Patterns on Soil Dissolved Organic Carbon and Microbial Biomass Carbon in Protected Field. *Sci. Agric. Sin.* **2010**, *43*, 1625–1633.
24. Yang, Y.; Niu, D.C.; Wen, H.R.; Zhang, B.L.; Dong, Q.; Chen, J.L.; Fu, H. Responses of soil particulate organic carbon and nitrogen along an altitudinal gradient on the Helan Mountain. *Inn. Mong.* **2012**, *21*, 54–60.
25. Hedley, M.J.; Stewart JW, B.; Chauhan, B.S. Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. *Soil Sci. Soc. Am. J.* **1982**, *46*, 970–976. [CrossRef]
26. Costa, M.G.; Gama-Rodrigues, A.C.; de Moraes Gonçalves, J.L.; Gama-Rodrigues, E.F.; da Silva Sales, M.V.; Aleixo, S. Labile and non-labile fraction of phosphorus and its transformation in soil under eucalyptus plantations. *Brazil. For.* **2016**, *7*, 15. [CrossRef]
27. Lin, X.G. *Principles and Methods of Soil Microbial Research*; Higher Education Press: Beijing, China, 2017.
28. Yu, F.Z.; Zhang, Z.Q.; Chen, L.Q.; Wang, J.X.; Shen, Z.P. Spatial distribution characteristics of soil organic carbon in subtropical forests of mountain Lushan, China. *Env. Monit Assess* **2018**, *190*, 545. [CrossRef]
29. Zhou, W.J.; Sha, L.Q.; Schaefer, D.A.; Zhang, Y.P.; Song, Q.H. Directs of litter decomposition on soil dissolved organic carbon and nitrogen in a tropical rainforest. *Soil Biol. Biochem.* **2015**, *81*, 255–258. [CrossRef]
30. Bargali, K.; Manral, V.; Padalia, K.; Bargali, S.S.; Upadhyay, V.P. Effect of vegetation type and season on microbial biomass carbon in Central Himalayan forest soils, India. *Catena* **2018**, *171*, 125–135. [CrossRef]
31. Xiang, Y.Z.; Chang, S.X.; Shen, Y.Y.; Chen, G.; Liu, Y.; Yao, B.; Xue, J.M.; Li, Y. Grass cover increases soil microbial abundance and diversity and extracellular enzyme activities in orchards: A synthesis across China. *Appl. Soil Ecol.* **2023**, *182*, 104720. [CrossRef]
32. Pang, D.B.; Cui, M.; Liu, Y.G.; Wang, G.Z.; Cao, J.H.; Wang, X.R.; Dan, X.Q.; Zhou, J.X. Responses of soil labile organic carbon fractions and stocks to different vegetation restoration strategies in degraded karst ecosystems of southwest China. *Ecol. Eng.* **2019**, *138*, 391–402. [CrossRef]

33. Golchina, A.; Oades, J.M.; Skjemstd, J.O. Soil structure and carbon cycling. *Aust. J. Soil Res.* **1994**, *32*, 1043–1068. [CrossRef]
34. Xiao, Y.; Huang, Z.G.; Lu, X.G. Changes of soil labile organic carbon fractions and their relation to soil microbial characteristics in four typical wetlands of Sanjiang Plain, Northeast China. *Ecol. Eng.* **2015**, *82*, 381–389. [CrossRef]
35. Wen, G.T.; De, X.C.; Phillips, O.L.; Liu, X.; Zhou, Z.; Li, Y.D.; Xi, D.; Zhu, F.F.; Fang, J.Y.; Zhang, L.M.; et al. Effects of long-term increased N deposition on tropical montane forest soil N_2 and N_2O emissions. *Soil Biol. Biochem.* **2018**, *126*, 194–203.
36. Hu, B.; Yang, B.; Pang, X.; Bao, W.; Tian, G. Responses of soil phosphorus fractions to gap size in a reforested spruce forest. *Geoderma* **2016**, *279*, 61–69. [CrossRef]
37. Zhou, J.; Wu, Y.H.; Bing, H.J.; Yang, Z.J.; Wang, J.P.; Sun, H.Y.; Luo, J. Variations in soil phosphorus biogeochemistry across six vegetation types along an altitudinal gradient in SW China. *Catena* **2016**, *142*, 102–111. [CrossRef]
38. Hou, E.Q.; Chen, C.R.; Lou, Y.Q.; Zhou, G.; Kuang, Y.; Zhang, Y.; Heenan, M.; Lu, X.; Wen, D. Effects of climate on soil phosphorus cycle and availability in natural terrestrial ecosystems. *Global Change Biol.* **2018**, *24*, 3344–3356. [CrossRef] [PubMed]
39. Ren, C.Q.; Wang, J.C.; Cheng, H.T.; Zou, Y.K. Effects of rubber (*Hevea brasiliensis*) plantations on soil phosphorus fractions and microbial community composition. *Acta Ecol. Sin.* **2017**, *37*, 7983–7993.
40. Liu, Y.J.; Wang, L.; Fan, W.; Ma, R.H.; Wang, F.; Xu, X.N. Effects of altitude on soil active organic carbon components in *Cunninghamia lanceolata* plantations. *J. Northwest A F Univ.(Nat. Sci. Ed.)* **2021**, *49*, 59–69.
41. Singh, D.; Takahashi, K.; Kim, M.; Chun, J.; Adams, J.M. A hump-backed trend in bacterial diversity with elevation on Mount Fuji, Japan. *Microb. Ecol.* **2012**, *63*, 429–437. [CrossRef]
42. Du, B.M.; Kang, H.Z.; Pumpanen, J.; Zhu, P.H.; Yin, S.; Zou, Q.; Wang, Z.; Kong, F.Q.; Liu, C.J. Soil organic carbon stock and chemical composition along altitude gradient in the Lushan Mountain, subtropical China. *Ecol. Res.* **2014**, *29*, 433–439. [CrossRef]
43. Li, S.; Zhang, S.; Pu, Y.L.; Li, T.; Xu, X.X.; Jia, Y.X.; Deng, O.P.; Gong, G.S. Dynamics of soil labile organic carbon fractions and C-cycle enzyme activities under straw mulch in Chengdu Plain. *Soil Till. Res.* **2015**, *155*, 289–297. [CrossRef]
44. Hodge, A.; Robinson, D.; Fitteg, A. Are microorganisms more effective than plants at competing for nitrogen? *Trends Plant Sci.* **2000**, *5*, 304–308. [CrossRef] [PubMed]
45. Xiang, H.M.; Wen, Z.D.; Zhang, L.L.; Li, J. Altitudinal changes in active and recalcitrant soil carbon pools of forests in the Dinghu Mountains. *Acta Ecol. Sin.* **2015**, *25*, 6089–6099.
46. Bunemann, E.K.; Marschner, P.; McNeili, A.M.; Mclaughlin, A.J. Measuring rates of gross and net mineralization of organic phosphorus in soils. *Soil Biol. Biochem.* **2007**, *39*, 900–913. [CrossRef]
47. Ma, H.F.; Xie, M.Y.; Hu, H.; Guo, Y.X.; Ren, C.J.; Zhao, F.Z. Effects of stoichiometric characteristics of soil-plant-litter on soil nitrogen components in different forests along an elevational gradient of Qinling Mountains. *Chin. J. Ecol.* **2020**, *39*, 749–757.
48. Bing, H.J.; Wu, Y.H.; Zhou, J.; Sun, H.Y.; Luo, J.; Wang, J.P. Stoichiometric variation of carbon, nitrogen, and phosphorus in soils and its implication for nutrient limitation in alpine ecosystem of Eastern Tibetan Plateau. *J Soils Sediments* **2016**, *16*, 405–416. [CrossRef]
49. Lin, H.Y.; Yuan, X.C.; Zhou, J.C.; Zeng, Q.X.; Sun, J.; Cheng, L.; Lin, K.S.; Xu, J.G.; Chen, Y.M. Effects of different elevational gradients on soil phosphorus fractions and availability in *Pinus taiwanensis* forest on Wuyi Mountain. *Acta Ecol. Sin.* **2021**, *41*, 5611–5631.