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Original Research

Effects of Planting Patterns on Soil Aggregates and Enzyme Activities in Rocky Desertification Areas of Karst Plateau Mountains

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Abstract

Soil aggregate characteristics and enzyme activities are key to the sustainable development of soil quality management. However, there are presently few studies on soil aggregate nutrients, enzyme activities, and their driving factors in areas with karst rocky desertification. As such, this study investigated the effects of planting patterns on soil aggregate nutrients and soil enzyme activities under six typical planting patterns (*walnut, Rosa roxburghii Tratt, ryegrass, walnut-Rosa roxburghii Tratt, Rosa roxburghii Tratt-ryegrass* and *walnut-ryegrass*) in the karst rocky desertification area of plateau mountains. The results indicated that: (1) there were significant differences in soil aggregate nutrients and soil enzyme activities among the different plots, when compared to traditional farmland, the increase in the aggregate nutrient content and soil enzyme activities was most noticeable in *walnut-Rosa roxburghii Tratt, Rosa roxburghii Tratt-ryegrass*, and *walnut-ryegrass*, and the nutrients gradually increased as the aggregate particle size decreased. The maximum C:N and C:P ratios were measured in the 0.25-2 mm aggregates, while the maximum N:P ratios was measured occurred in the <0.053 mm aggregates. (2) The stoichiometric ratios had different degrees of relevance associated with the aggregate nutrients, TN and C:N, SOC and C:P, and TP and N:P showed extremely significant linear correlations. Moreover, a significant correlation also occurred between enzyme activity and aggregate nutrients, particularly in macroaggregates. (3) Soil physicochemical properties, such as the soil total porosity, capillary water holding capacity, saturated hydraulic conductivity, bulk density and pH, had a direct influence on enzyme activity, therefore, the soil condition can be improved by changing the planting patterns to promote enzyme activity. These findings are helpful for the optimal allocation of forest and grass for the comprehensive control of karst rocky desertification.

Keywords: planting pattern, soil aggregate, soil enzyme activity, ecological stoichiometry, karst rocky desertification

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Introduction

Special geographical environment and long-term human impacts have led to extensive degradation of surface soil and serious rocky desertification in the karst region of South China, which has become an important ecological problem affecting social and economic development [1]. Along with the implementation of governance measures such as closing hillsides to facilitate afforestation, ecological forest management, and grassland transformation [2], it has assisted in alleviate the human-land contradiction and promote the economic development to some extent.

Carbon, nitrogen and phosphorus in soil are important elements for maintaining the growth of surface plants [3], which directly affects the supply, transformation and sequestration capacity of carbon, nitrogen and phosphorus in terrestrial ecosystems [4]. As the basic unit of soil structure [5], soil aggregates can regulate water, fertilizer, gas and heat in the soil and maintain and stabilize the soil layers [6]. The contents of aggregates of different particle sizes are significantly associated with the changes in soil organic carbon (SOC), total nitrogen (TN) and total phosphorus (TP) [7]. Nevertheless, there are still different views on nutrient allocation among soil aggregates with different particle sizes. By studying the changes in the total nutrient contents of carbon, nitrogen and phosphorus in soil aggregates of five sample plots in different years, Ou et al. [8] reported that, during the vegetation restoration process, the contents of carbon, nitrogen and phosphorus increased with the decreasing soil aggregate particle size. Similar results were obtained by Pan et al. [7], who found that the amount of phosphorus in soil aggregates became the limiting element in the restoration of eroded red soil vegetation. However, some researchers hold different views, Gale et al. [9] indicated that the particle size of soil aggregates was positively correlated with the distribution of total nutrients base on a simulated no-till study. Concurrently, it reflects the heterogeneity and complexity of the influences of soil aggregates.

Ecological stoichiometry is considered as an important indicator to study the energy balance of biological systems and soil elements (carbon, nitrogen, phosphorus) [10], while the stoichiometric characteristics of carbon, nitrogen and phosphorus in soil aggregates are an important way to study the nutrient cycles of ecosystems and to reveal the supply and maintenance capacity of soil nutrients [11] Due to the influence of regional environmental changes, soil-forming processes and human activities, the stoichiometric ratios of carbon, nitrogen and phosphorus exhibit obvious spatial variability [12]; the mean stoichiometric ratios of C, N and P in global surface soil are approximately 186:13:1 [13], and the ratios of C:N, C:P and N:P in the surface soil of China are 12.3, 52.7 and 3.9, respectively [14]. As the main carrier of soil nutrient storage and transformation [15], it is necessary to investigate the ecological stoichiometric characteristics of soil aggregate SOC, TN and TP in rocky desertification areas.

Soil enzymes, as important catalysts in the soil ecosystem, may rapidly reflect the direction and intensity of the change in the chemical characteristics of substances in the processes of material cycling and energy conversion [16]. What is worth mentioning is that soil enzymes play a key role in the cycles and morphological transformations of carbon, nitrogen and phosphorus in the soil [17], and can sensitively respond to the changes in vegetation coverage [18]. Some studies have confirmed that the levels of soil enzyme activity can be applied to represent the soil quality [19], the soil enzyme activity increases with vegetation restoration [20], and soil nutrients may be closely related to soil enzyme activity [21]. However, few studies have been carried out by combining soil enzyme activity with soil conditions in rocky desertification areas. Consequently, the analysis of nutrient changes, stoichiometric characteristics and enzyme activity levels in soil aggregates would be an effective way to reflect the effect of vegetation restoration in karst rocky desertification areas.

Currently, there is a multitude of studies on soil nutrients and enzyme activities, such as the effects of changes in different land-use types [22], fertilization models [23], biochar and straw mulching [24], tree species and enzyme activities [25] on soil nutrients. Planting patterns lead to differences in soil environmental factors, which in turn, affect soil aggregate nutrients and enzyme activities. However, few studies have been conducted on soil aggregate nutrients and enzyme activities in karst areas. Therefore, six planting events were investigated to further understand the interrelationships between aggregate nutrients and enzyme activity and the driving factors. The specific objectives of this study are as follows: (1) to analyse differences in soil aggregate nutrients and enzyme activities under different planting patterns; (2) to explore the relationship between aggregate nutrients and enzyme activity under different planting patterns; and (3) to reveal the effects of soil environmental factors on soil aggregate nutrients and enzyme activities.

Materials and Methods

Study Area

The Bijie Salaxi Demonstration Area of Karst Rocky Desertification Comprehensive Control (105°01’12”-105°08’38”E, 27°11’09”-27°17’28”N) is located in the Liuchong River basin, a tributary of the upper reaches of the Wujiang River. Karst landforms cover 73.94% of the total area, and the rocky desertification grade is mainly potential-moderate. This area has a subtropical monsoon humid climate, with an average annual temperature of 12.7ºC and an average annual rainfall of 984.40 mm. Yellow soil is the predominant soil type, with mountain yellow brown soil and calcareous soil being found in some areas, and the average thickness of the soil layer is 20 cm, with thicker soil developing in some depressions. Since ecological management of karst rocky desertification was implemented in this area, traditional farming planting activities have gradually been modified into other planting patterns such as commercial varieties and grasslands. Because of the faster growth rate and larger size of *walnut*, *Rosa roxburghii Tratt,* and *ryegrass,* a typical forest-grass vegetation planting pattern has resulted.

Experimental Design

Based on the current situation of the artificial forest and grass vegetation restoration mode in the ecological control project of rocky desertification, taking the traditional agricultural cultivated land (corn) as the control, we selected six planting patterns (*walnut, Rosa roxburghii Tratt, ryegrass, walnut-Rosa roxburghii Tratt, Rosa roxburghii Tratt-ryegrass* and *walnut-ryegrass*) with yellow soil as the background in the study area. In April 2019, three 10 m × 10 m plots were arranged in each sample area, and 5 sampling points based on an S-shape were established. Soil was collected from each profile with a 100-cm^3 ring knife at soil depth of 0-10 cm and 10-20 cm, and approximately 1 kg of undisturbed soil was taken at the different depths of each sampling point. Each soil sample was immediately placed into a PE plastic bag and sealed, and transported to the lab in an ice box for physical and chemical properties measurements. The details of the selected samples are displayed in Table 1.

Soil Sample Treatment and Determination Methods

The wet sieving method was employed to pretreat and screen soil samples because it is more reproducible [26] and may better reflect the distribution and stability characteristics of soil aggregates [27]. A 10 mm sieve was used to sieve the naturally air-dried soil samples, and 50 g of each sample was selected, sieved, and then statically placed in water. After the soil sample was wetted for 10 minutes, an aggregate analyser (XY-100) was used to separate the aggregates: >2 mm, 0.25-2 mm, 0.053-0.25 mm, and <0.053 mm aggregates were sieved and dried at 40ºC (accurate to 0.01 g). To obtain the average value, the treatment process was repeated three times. Simultaneously, soil aggregate samples from all levels obtained by wet sieve analysis were passed through a 100-mesh sieve to measure the SOC, TN and TP contents.

SOC content was determined by the potassium dichromate volumetric method-oil bath method (GB7857-87), TN content and TP contents were determined by digestion with sulfuric acid-potassium sulfate: copper sulfate (9:1) and sulfuric acid-perchloric acid, respectively, and the extracted filtrates were analysed by a continuous flow analyser (SEALAA3, Germany) [28]. Soil enzyme activities were assayed according to the methods described by Guan et al. [29]. Urease activity was determined by the phenol-sodium hypochlorite colorimetric method at 578 nm using a purple spectrophotometer, sucrase activity was determined by the 3,5-dinitrosalicylic acid colorimetric method at a wavelength of 508 nm, and acid phosphatase activity was determined by the disodium phenyl phosphate colorimetric method at a wavelength of 570 nm.

Table 1. Basic information of sample plots.

Sample plot	Longitude	Latitude	Altitude/m	Slope Inclination/◦	Slope Aspect	Land-Use
Corn (C)	105°06′38″E	27°15′10″N	1760	17	Half shady slope	Still growing corn
Walnut (W)	105°05′21″E	27°15′41″N	1879	15	Half shady slope	Returning farmland, planting in 2010
Rosa roxburghii Tratt (RT)	105°06′20″E	27°14′21″N	1813	18	Half shady slope	Returning farmland, planting in 2010
Ryegrass (R)	105°05′35″E	27°14′17″N	1773	12	Half shady slope	Returning farmland, planting in 2009
Walnut-Rosa roxburghii Tratt (WRT)	105°06′13″E	27°13′44″N	1751	14	Half shady slope	Returning farmland, planting in 2009
Rosa roxburghii Tratt -*Ryegrass* (RTR)	105°06′08″E	27°14′49″N	1826	16	Half shady slope	Returning farmland, planting in 2010
Walnut-Ryegrass (WR)	105°06′27″E	27°12′35″N	1892	19	Half shady slope	Returning farmland, planting in 2010

Data Analysis

We used SPSS 22 (IBM Corp., Armonk, New York, USA) and Excel 2010 (Microsoft Corp., Albuquerque, NM, USA) to complete the statistical analysis. One-way analysis of variance (ANOVA) was used for difference analysis, and the least significant difference (LSD) method was used for multiple comparisons and binary analysis of variance at the 0.05 level. Two-way ANOVA was used for interaction analysis. The Pearson coefficient was used for correlation analysis. Redundancy analysis (RDA) was applied to explore the relationship between environmental factors and soil aggregate nutrients and enzyme activities. All figures in this article were generated using Origin 2018 (OriginLab Crop., Northampton, MA, USA) and Canoco 5.0 (Microcomputer Power, Ithaca, NY, USA).

Results

Characteristics of Soil Aggregate Nutrients and Enzyme Activity

Soil Aggregate Nutrients

Under the different planting patterns (Fig. 1a and 1b), the SOC content of the soil aggregates varied from 22.72 g/kg to 60.67 g/kg, with the 0-10 cm soil layer having a higher SOC content than the 10-20 cm soil layer. In the 0-10 cm soil layer, the SOC content of the 4-level aggregates in W and RTR was evidently higher than that in C; additionally, it was significantly different from R in the particle sizes of >2 mm, 0.25-2 mm, and <0.053 mm, and the SOC content of microaggregates was higher than that of macroaggregates. Nevertheless, the variation trend of the aggregate SOC content in the 10-20 cm soil layer was different from that in the 0-10 cm soil layer. RTR had the highest SOC content of the four aggregates classes, whereas C had the lowest.

According to Fig. 1c) and 1d), the TN content of soil aggregates under different planting patterns ranged from 0.93-3.36 g/kg. Except for the fact that the TN content of RT in the 10-20 cm soil layer was slightly lower than that of WRT, the variation along the vertical profile was similar to that of SOC. RTR, WRT and WR had high TN contents in all particle sizes. In the three particle sizes of 0.25-2 mm, <0.053 mm and 0.053-0.25 mm, the TN content of WR was significantly different from that of C

The TP content ranged from 0.67 g/kg to 1.80 g/kg (Fig. 1e and 1f), with the 10-20 cm soil layer having a somewhat lower TP content than the 0-10 cm soil layer. Although the variation of the TP content among the different planting patterns did not exhibit an obvious pattern, the TP content increased with decreasing particle size within the same planting pattern. Except for RT and WR, the remainder of the plots presented an increase compared with C.

Stoichiometry of Soil Aggregates

In the 0-20 cm soil layer, the variation range of the C:N ratio of the soil aggregates in the different plots was 12.09~44.18 (Fig. 2a and 2b), and the average value was 18.93. Moreover, the content of the four-particle sizes in R was slightly higher than that in other plots, and the C:N ratio distribution of the same particle size in different plots exhibited an obvious difference.

The C:P ratio varied from 17.81 to 59.96 among different plots (Fig. 2c and 2d), with an average value of 40.11. There were obvious differences in the variation dynamics of the C:P ratio of each particle size in the 0-10 cm and 10-20 cm soil layers. At 0-10 cm, the variation range of the C:P ratio of each particle size aggregate was 19.97-48.14, 19.74-55.18, 22.48-49.08, and 17.81-56.08, respectively. In contrast, in the 10-20 cm soil layer, the C:P ratios of RTR in the >2 mm, 0.25-2 mm and 0.053-0.25 mm particle sizes were significantly higher than those of R, C and WRT.

In the different types of plots, the N:P ratio in the microaggregates and moderately aggregates was higher than that in the macroaggregates, and the N:P ratio in aggregates of different sizes was significantly different (Fig. 2e and 2f). WR was patently different from C and R with respect to the two aggregate sizes of >2 mm and 0.25-2 mm at 0-10 cm,, while the N:P ratios were 0.053-0.25 mm and <0.053 mm, and WR was significantly different from C, W and R. At 10-20 cm, the maximum N:P ratios of the >2 mm and 0.25-2 mm aggregates were measured in RT and were visibly higher than those measured in C and R. The maximum N:P ratios in the 0.053-0.25 mm and <0.053 mm aggregates appeared in WR, but the difference from C was not significant.

Soil Enzyme Activities

Soil urease and acid phosphatase activities increased to a certain extent after the conversion of C to different planting patterns (Fig. 3). In the 0-10 cm soil layer, the urease activity of the different types of plots was between 1.26 and 1.48 mg/g, among which WR was significantly different from that of the other plots. Urease activity was slightly lower in the 10-20 cm soil layer than in the 0-10 cm soil layer, and its variation range was smaller. In the 10-20 cm soil layer, the urease activity was the highest (1.40 mg/g) in WRT, the lowest (1.27 mg/g) in C, and WRT had significantly higher urease activity in than that in W, WR, R, RTR and C.

In the 0-10 cm soil layer, the soil acid phosphatase activity of each plot varied between 0.82 and 1.15 mg/g, among which WR was significantly different from RT and C. The acid phosphatase activity in the 10-20 cm soil layer ranged from 0.80 mg/g to 1.07 mg/g, which was lower than that in the 0-10 cm soil layer. Among them, the decreases in WR and W were small. C had the lowest acid phosphatase activity and WR had

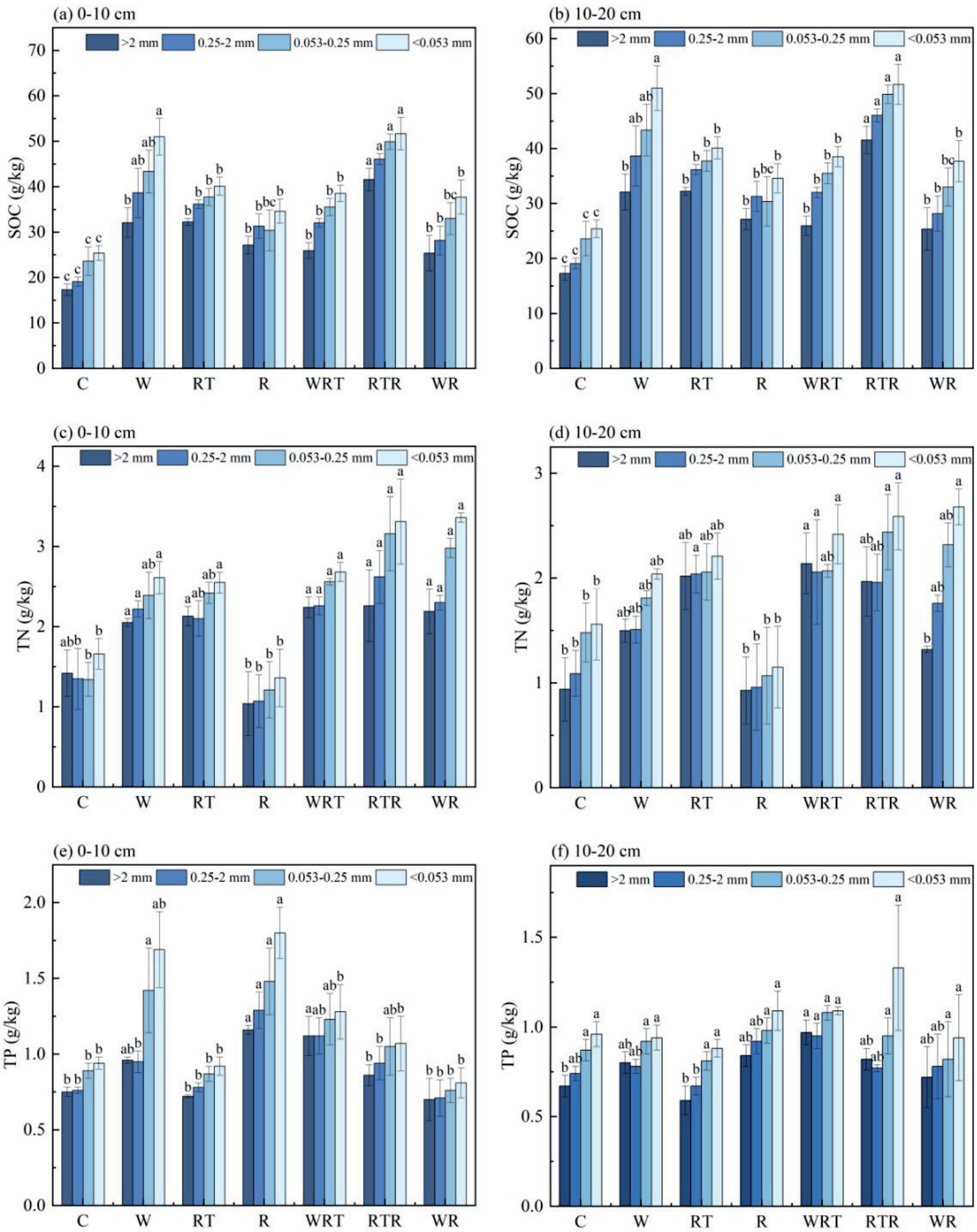

Fig. 1. Nutrient distribution characteristics of soil aggregates under different planting patterns. C: *corn*, W: *walnut*, RT: *Rosa roxburghii Tratt*, R: *ryegrass*, WRT: *walnut-Rosa roxburghii Tratt*, RTR: *Rosa roxburghii Tratt-ryegrass*, WR: *walnut-ryegrass*, SOC: soil total organic carbon, TN: total nitrogen, TP: total phosphorus. Different lowercase letters indicate significant differences (p<0.05). Same below.

the highest, while the acid phosphatase activities of the other plots were significantly different from those of C.

Soil sucrase activity ranged from 16.81 to 55.20 mg/g among the seven plots. At 0-10 cm, compared with C, the sucrase activity of WRT, W, WR and R increased by 1.53, 0.77, 0.30 and 0.17 times, respectively, and there were significant differences among WRT, W and C. The sucrase activity in the 10-20 cm soil layer was in a state of decline; the specific variation range was between 13.15 mg/g and 36.68 mg/g, of which the decrease in WRT was the largest, and the sucrase activity in WRT was significantly higher than that in RT, R, RTR, WR and C.

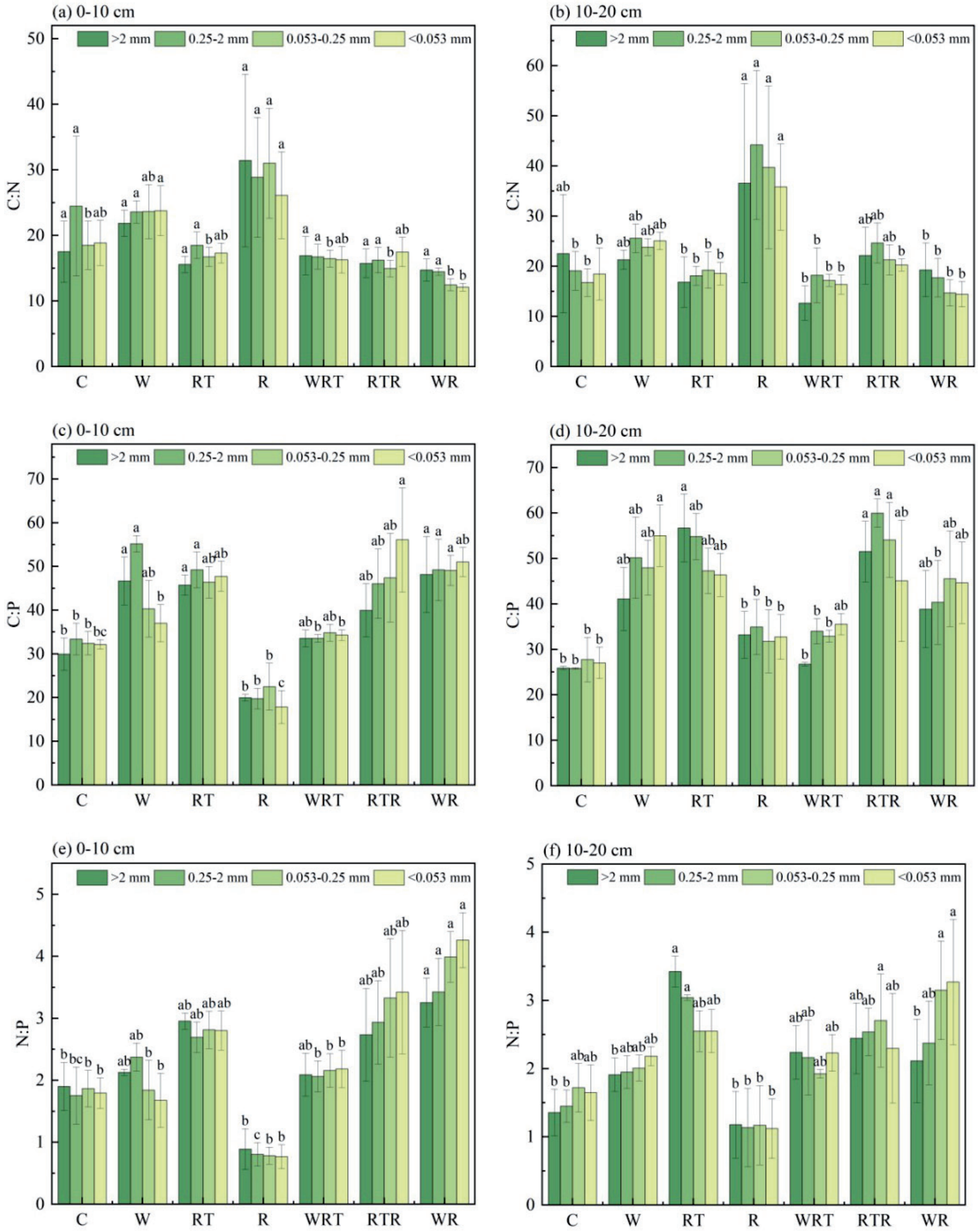

Fig. 2. The stoichiometric ratio of soil aggregates under different planting patterns. C:N: the ratios of soil total organic carbon to total nitrogen, C:P: the ratios of total organic carbon to total phosphorus, N:P: the ratios of total nitrogen to total phosphorus. Same below.

Correlation Analysis between Soil Aggregate Nutrients and Enzyme Activity

Correlation Analysis between Soil Aggregate Nutrients and the Stoichiometric Ratio

Under different planting patterns and different aggregate particle sizes, there was an exceedingly significant positive correlation between SOC and TN ($p<0.01$) (Table 2). Fig. 4 demonstrates that there were certain correlations between soil SOC, TN, TP and the corresponding stoichiometric ratios, but the significance levels were different. Among them, TN and C:N, N:P, SOC and C:P, and TP and N:P had extremely significant linear correlations ($p<0.001$).

Correlation Analysis between Soil Aggregate Nutrients and Enzyme Activity

The two-way ANOVA results of the effects of the different planting patterns and soil nutrients on the soil enzyme activities indicated that there were intensely

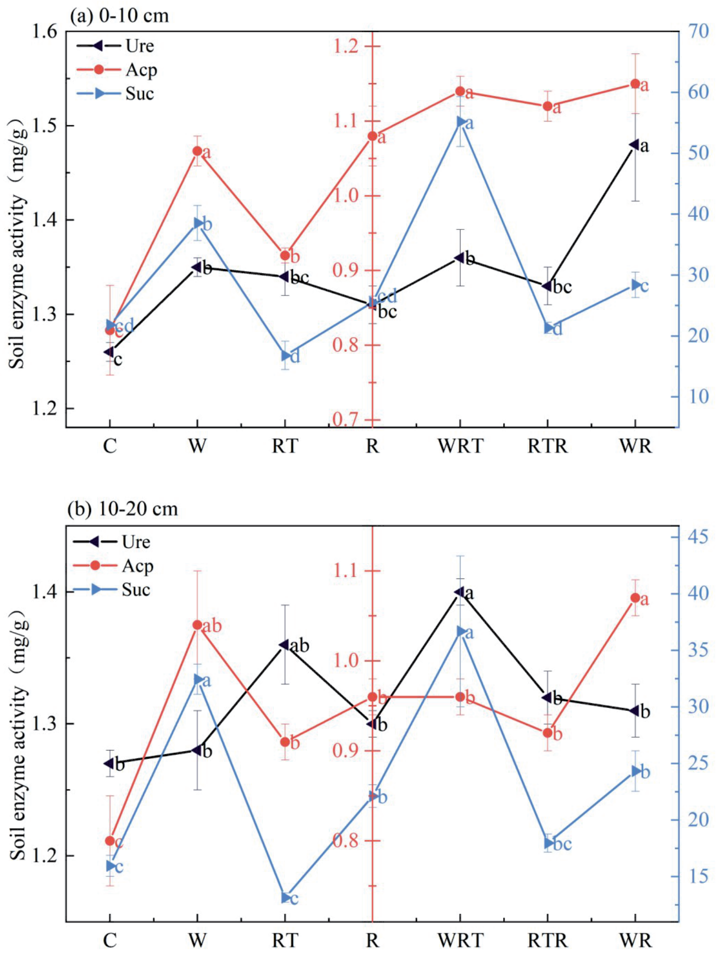

Fig. 3. Characteristics of soil enzyme activities under different planting patterns. Ure: the urease activity, Acp: the acid phosphatase activity, Suc: the sucrase activity. Same below.

obvious differences in these activities under the single and interactive effects of planting patterns and soil nutrients ($p < 0.01$).

According to the results of the correlation analysis between aggregate nutrients and enzyme activity under the different planting patterns (Fig. 5), the TP content of the >2 mm aggregates (Fig. 5a) was extremely significantly correlated with the acid phosphatase activity and sucrase activity (p<0.01). Moreover, the TN content was extremely significantly related to the urease activity (p<0.01), and the SOC content was significantly related to the sucrase activity (p<0.05). In the 0.25-2 mm aggregates (Fig. 5b), TN was extremely significantly correlated with urease activity (p<0.01), while TP was extremely significantly correlated with acid phosphatase activity ($p < 0.01$). TN was extremely significantly positively correlated with urease activity in the 0.053-0.25 mm particle size group (p<0.01, Fig. 5c), and TP was extremely positively related to the sucrase activity (p<0.01). In the < 0.053 mm aggregates (Fig. 5d), TN was extremely significantly positively correlated with urease activity and acid phosphatase activity (p<0.01), and the interrelationship between the soil enzyme activity and the macroaggregates was higher than that of other particle aggregates.

Table 2. Correlation analysis of SOC, TN and TP of aggregates with different particle sizes.

	>2 mm		0.25-2 mm		0.053-0.25 mm		<0.053 mm	
	TN	TP	TN	TP	TN	TP	TN	TP
SOC	0.538**	0.162	0.519**	-0.015	0.496**	0.190	0.508**	0.191
TN	1	0.030	1	-0.044	1	-0.152	1	-0.226

** indicates a significant correlation at the 0.01 level. * indicates a significant correlation at the 0.05 level.

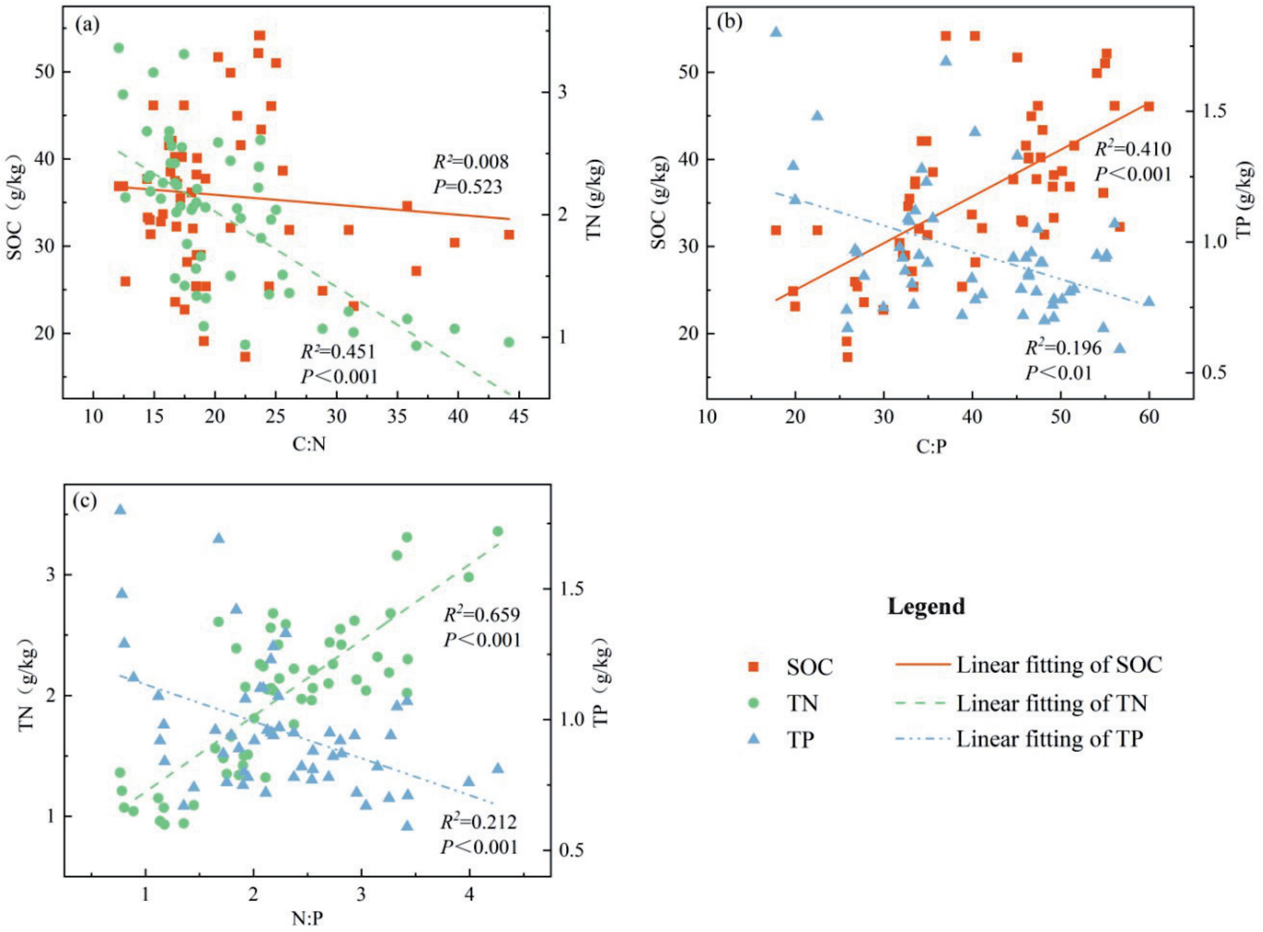

Fig. 4. Relationship between soil aggregate C, N, P and stoichiometric ratio.

Effects of Environmental Factors on Soil Aggregate Nutrients and Soil Enzyme Activities

Effects of Planting Patterns and Soil Depth on Soil Aggregate Nutrients and Soil Enzyme Activities

Planting pattern and soil depth had marked effects on SOC, C:N and urease activity (p<0.05) (Table 3), and extremely significant effects on TN, TP, acid phosphatase activity and sucrase activity (p<0.01). The interaction between planting pattern and soil depth had significant effects on soil N:P and acid phosphatase activity (p<0.05), and extremely significant effects on SOC, TP, C:P and urease activity (p<0.01).

Effects of Environmental Factors on Nutrients in Soil Aggregates

RDA of the soil environment for aggregates C, N, and P and their stoichiometric ratios indicated (Fig. 6) that the first axis explained 34.24% and the second axis explained 6.92%. The two-dimensional sorting demonstrates that the aggregate SOC was mainly affected by saturated hydraulic conductivity, organic matter, available phosphorus and available nitrogen, and was positively correlated with these factors; in contrast, SOC was negatively correlated with the natural water content and capillary porosity. Furthermore, the TN of the aggregates was positively associated with the bulk density and negatively correlated with the total porosity. TP was positively correlated with pH, organic matter and SOC. The C:N value was positively correlated with pH, total porosity and capillary porosity; the C:P value was positively correlated with saturated hydraulic conductivity but negatively correlated with capillary porosity; and the N:P value was positively correlated with bulk density but negatively correlated with pH and total porosity. These results indicated that the soil environment was an important driving factor affecting changes in the soil aggregate C, N, and P and their stoichiometric ratios.

Effect of Environmental Factors on Soil Enzyme Activity

Fig. 7 illustrates that the explanation rates of the three enzyme activities on the first axis and the second axes were 65.07% and 0.85%, respectively; that is, the 12 environmental factors in the first two axes of RDA explained 65.92% of the soil enzyme activity characteristics. The arrows connecting the soil saturated hydraulic conductivity, SOC, organic matter, and

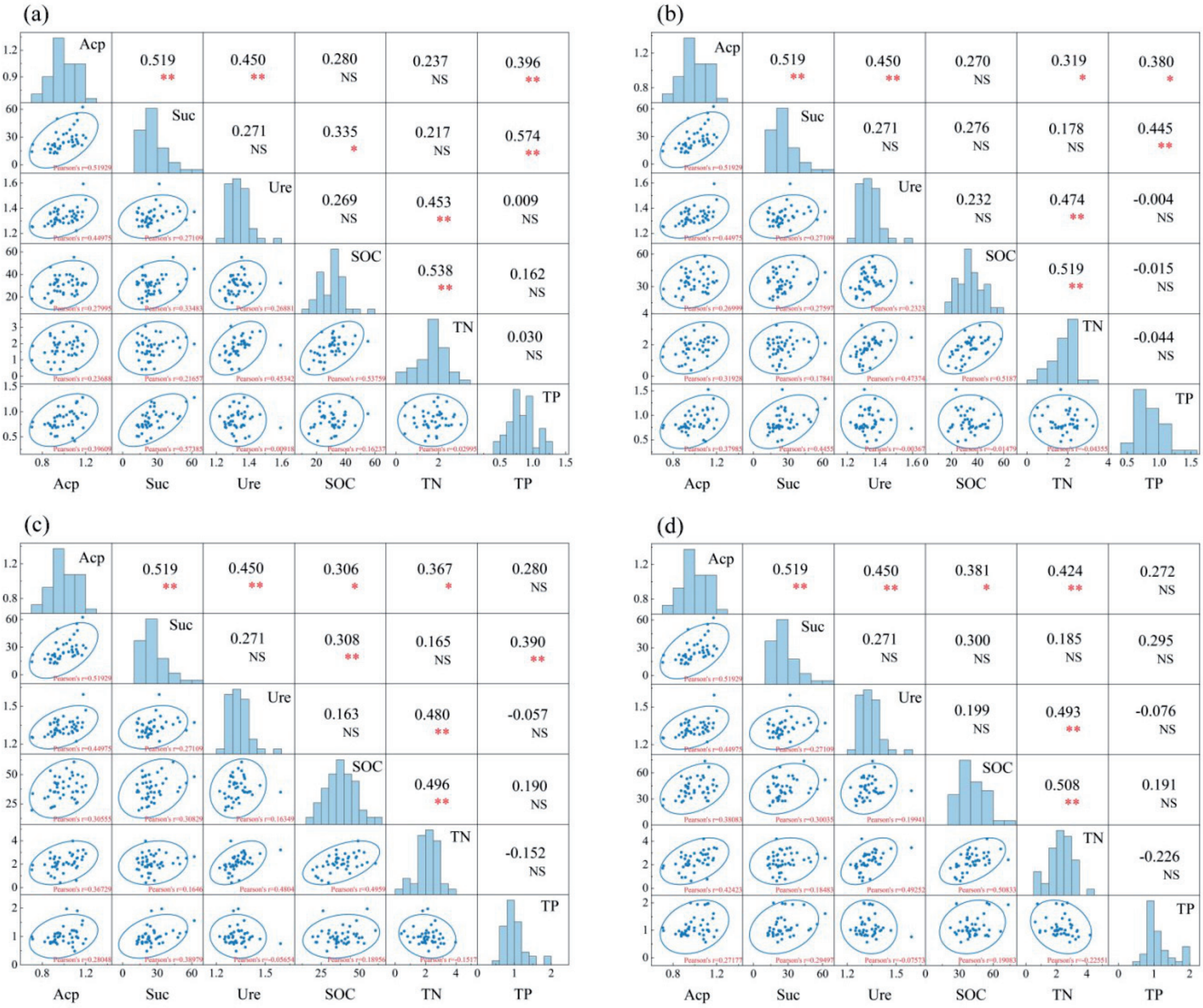

Fig. 5. Relationship matrix between soil aggregate nutrients and enzyme activity.

natural water content were the longest, indicating that the three factors played a powerful role in explaining the differences in enzyme activities. Among them, the TN, total porosity, capillary porosity and saturated hydraulic conductivity were consistent with the direction of the urease activity arrow and the included angle was small, indicating a positive connection, while it had a prominent negative correlation with bulk density. The saturated hydraulic conductivity was consistent with the direction of the acid phosphatase activity, total porosity, and capillary porosity and presented a significant positive correlation, and the saturated hydraulic conductivity was the dominant factor affecting the acid phosphatase activity. Sucrase activity was positively correlated with SOC, organic matter, pH and the natural water content.

Discussion

Relationships between Nutrients and Enzyme Activities of Aggregates

Soil enzymes are mainly derived from animal and plant residues, root exudates and microbial activities. The level of enzyme activity can indicate

Table 3. Two-way ANOVA of soil aggregate nutrients and enzyme activities according to planting pattern and soil depth.

	SOC	TN	TP	C:N	C:P	N:P	Ure	Acp	Suc
Planting pattern	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Soil depth	0.00	0.00	0.00	0.03	0.23	0.07	0.03	0.00	0.00
Planting pattern × Soil depth	0.00	0.29	0.00	0.23	0.01	0.03	0.01	0.02	0.06

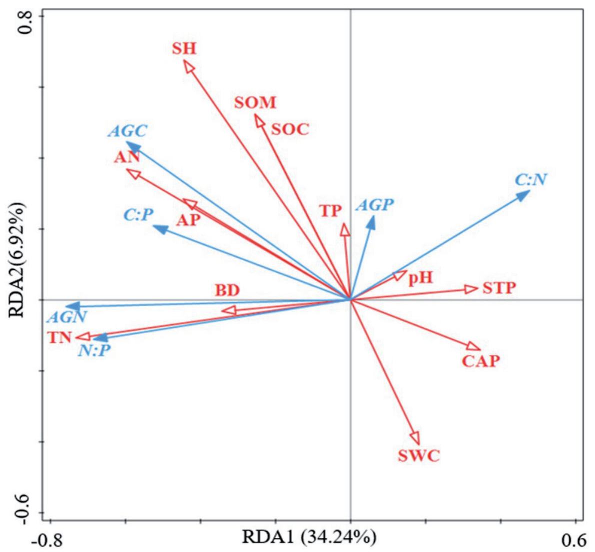

Fig. 6. Redundancy analysis of the effects of soil environmental factors on soil aggregate C, N, and P and their stoichiometric ratios. BD: bulk density, SWC: soil natural water content, CP: capillary water holding capacity, SH: saturated hydraulic conductivity, STP: soil total porosity, CAP: capillary porosity, SOM: soil organic matter, SOC: soil organic carbon, TN: total nitrogen, STP: total phosphorus, AN: available nitrogen, AP: available phosphorus, AGC: aggregate organic carbon, AGN: aggregate total nitrogen, AGP: aggregate total phosphorus.

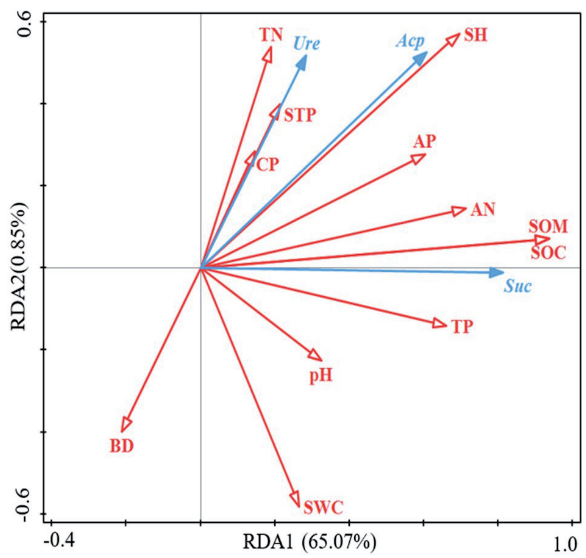

Fig. 7. Redundancy analysis of soil enzyme activity and soil environmental factors.

the circulation of soil nutrients. Various factors affect soil enzyme activity and are closely related to soil properties [21]. In addition, human factors such as land-use types, soil farming systems and management methods affect soil enzyme activities [30]. Soil enzymes are also affected by the aggregate formation environment, internal nutrients and water differences; the particle size also affects the intensity of nutrient transformation by affecting the microorganisms and soil enzymes in the aggregate microenvironment [31]. Aggregates have an obvious protective effect on soil enzymes, and the transformation of various organic and inorganic substances in soil aggregates depends on the corresponding soil enzymes. As important elements of soil, SOC, TN and TP can change the soil permeability, temperature and structure and can transport nutrients for plant growth, which is closely related to soil enzyme activity.

In this study, the main influential factors of the three enzyme activities were SOC, TN, TP, saturated hydraulic conductivity, and porosity, similar to a study conducted by Cui et al. [21]. SOC, acid phosphatase and sucrase were significantly correlated; TN was significantly correlated with urease and acid phosphatase; TP and sucrase were extremely significantly correlated; and acid phosphatase was strongly correlated. This study indicated that the connection between soil enzyme activity and macroaggregates was higher than that of other particle size aggregates, which is consistent with the research results of Ji et al. [20] and Ma et al. [32]. Because the higher decomposition rate of organic matter in microaggregates is not conducive to the accumulation of soil nutrients, sufficient substrates in macroaggregates can increase enzyme activity, and substrate organic carbon in macroaggregates is a type of readily decomposed active organic carbon, while substrate organic carbon in microaggregates is inert and difficult to decompose [33, 34], thereby further reinforcing the enzyme activity in macroaggregates [6].

From the perspective of the formation of soil aggregates, the clay particles in the microaggregates have an adsorption effect on soil enzymes and inhibit the catalytic ability of soil enzymes, while the enzyme in the large particle aggregates have higher catalytic activities, which can effectively degrade organic matter and release nutrients. There were differences in the enzyme activity and nutrient cycling in aggregates with different particle sizes [35]. The results indicated that the changes in enzyme activity were closely related to the soil environment, and the conversion of planting patterns improved the soil condition, thus producing a good promotion effect on enzyme activity. Nevertheless, since the changes in soil enzyme activities have not yet demonstrated obvious differences and uniform principles, in-depth and long-term research is still required on the enrichment of biogenic substances in soil aggregates and the carbon and nitrogen cycles during the restoration of karst rocky desertification areas in this region still require reasearch.

Responses of Soil Aggregate Nutrients and Enzyme Activities to Planting Patterns

The SOC, TN and TP contents were used to determine the main fertility index of the soil [36]. Soil aggregates, as the material basis for maintaining and supplying soil fertility, are closely related to soil quality, biological activity and permeability [37]. Due to the different constituent substances in different particle size aggregates, their maintenance and supply roles in carbon, nitrogen and phosphorus nutrient cycling are different [38]. In this study, the SOC, TN, and TP contents were the highest in WRT, which is consistent with the research results of Meng et al. [39]. Furthermore, the contents of SOC and TN in the soil aggregates of W, RT, WRT, RTR and WR were significantly higher than those in C, indicating that the vegetation restoration measures implemented in the study area have effectively improved the ability of soil to retain carbon and nitrogen by increasing the vegetation coverage and increasing the source of organic matter. Because of the direct effects of fertilization and tillage activities on the soil surface and the increase in exogenous nutrient input due to crop plant residues and tillage [40], nutrients first accumulated in the upper soil layer, resulting in the carbon and nitrogen contents and aggregates in the 10-20 cm soil layer being lower than those in the 0-10 cm soil layer, while the TP content in each particle size aggregate changed slightly because phosphorus was derived from the soil parent material and the change was relatively stable [15]. The distribution of the SOC, TN, and TP contents demonstrated that the content of microaggregates was higher than that of macroaggregates, which may be the reason for fertilization in tillage practies [41], and some studies have indicated that there is a strong positive correlation between the contents of carbon, nitrogen and phosphorus in macroaggregates and microaggregates [42, 43]. The macroaggregates had a higher accumulation rate, but the microaggregates were more stable [44]. In addition, the nutrient absorption capacity of the soil aggregates was proportional to the specific surface area [45]. At the same mass, the smaller the particle size of the soil aggregate, the larger the specific surface area, and the nutrient turnover time in the microaggregates was longer than that in the macroaggregates [46].

The soil C:N ratio is an important parameter affecting the degradation of soil organic matter [47]. Our research discovered that the variation range of the soil C:N ratio in the different types of plots was between 9.39 and 20.61, with an average value higher than that of national terrestrial soil (12.3) [14], and the ratio in which C was significantly higher than that in RT, RTR and WR. These discrepancies may result from the artificial fertilization measures of agricultural land causing the SOC content to increase more rapidly, while the TN content increased very slowly. Compared with C, the C:N ratio of aggregates in different plots increased to a certain extent; the higher C:N ratio of aggregates was mainly due to the slow decay rate of organic matter, which directly affected the accumulation of nitrogen [48]. Furthermore, the soil C:N ratio increased with decreasing aggregate particle size, which may be due to the poor stability of macroaggregates [49]. According to Six et al. [6], macroaggregates are formed by the combination of multiple microaggregates and binders, allowing them to protect more particulate SOC and organic matter. In this study, the C:N in microaggregates was lower than that in macroaggregates, indicating that the higher decomposition rate of organic matter in the microaggregates was not conducive to the accumulation of soil nutrients.

Soil C:P is generally considered to be a marker of soil phosphorus mineralization or an indicator of the potential to absorb and immobilize phosphorus from the environment, whereas N:P reflects soil fertility and directly affects the bioavailability of soil nutrients [50], and is an important indicator used to measure the limitation of nutrients in various habitats [51]. The research results revealed that the variation range of the aggregate C:P ratio in the different plots was 17.81-59.96, and the average value was lower than that of the national land (the C:P ratio in China is 61, and the N:P ratio is 3.9) [14]; SOC and TP had extremely strong associations with the C:P ratio, while TP had a higher correlation, indicating that soil aggregate TP had a greater impact on the C:P ratio and demonstrated an increasing trend with the decrease in particle size. Meanwhile, the effect of plantation-grass vegetation restoration on the increase in the soil C:P ratio was mainly reflected in aggregates with a particle size of <0.25 mm; a trend of phosphorus assimilation by microorganisms in macroaggregates was also reflected [52]. Nitrogen and phosphorus were the main limiting elements in the soil ecosystem. Wang and Yu [12] reported that N:P is an important indicator for predicting the type of soil nutrient limitation. In this study, the N:P ratio of the aggregates at the different sites ranged from 0.77 to 4.26, and the maximum value appeared when the regularity of its changes was poor, reflecting that nitrogen and phosphorus were in unstable states during the process of nutrient accumulation and consumption.

Soil enzyme activity, as a catalyst for nutrient transformation and cycling, plays a key role in soil biochemical function, nutrient cycling, and litter and artificial substance degradation [53]. In our work, the content of urease was highest in WRT and WR, and sucrase activity was the highest in WRT. There was no marked difference in the content of acid phosphatase activity in the sample plots except for C and RT, which may be due to their more developed plant root systems, richer litter and higher microbial content in WRT and WR than in R and C; these factors encourage good soil environment formation, promote nutrient accumulation and cyclic metabolism, enhance soil enzyme activity and are consistent with the conclusions of Rudinskienė et al. [54] and Olatunji et al. [55]. Therefore, in the process of vegetation restoration in karst rocky desertification areas, agricultural activities may be somewhat restricted in their ability improve soil quality, but forests can better conserve soil and water and increase soil enzyme activity.

The RDA results revealed that soil nutrients were significantly influenced by soil environmental factors, and there were correlations between soil enzyme activity and both soil environmental factors and soil nutrients. STP, CP, SH, pH, and BD were important factors that affected enzyme activity in this study, indicating that soil enzyme activity in the study area is closely related to changes in soil environmental dynamics. Changes in planting patterns improve the physical structure of the soil and enhance soil porosity, water retention, and the soil water content, and also change the soil bulk density and pH, which are more suitable for soil microbial metabolic activities and enzyme production [21].

Conclusions

Planting patterns had a distinct effect on the soil aggregate nutrient content, stoichiometric ratio and enzyme activity, effectively increasing the contents of SOC, TN and TP in soil aggregates and the activities of soil urease, invertase and acid phosphatase. Compared with those of other planting patterns, the nutrient contents of *walnut-Rosa roxburghii Tratt* and *Rosa roxburghii Tratt-ryegrass* were higher, and the enzyme activities of *walnut-Rosa roxburghii Tratt* and *walnut-ryegrass* increased significantly. From the perspective of aggregate particle size, the nutrient content of microaggregates was higher. Aggregate SOC and TN interacted with each other, and the stoichiometric ratio had different degrees of relevance with the corresponding nutrients, allowing for the desired effect of improving the soil environment by changing important nutrients. There was also a strong correlation between the aggregate nutrients and enzyme activity. Enzyme activity can be improved in the management of karst rocky desertification areas by enhancing the content of soil nutrients and macroaggregates. Aggregate nutrients and enzyme activities are intimately connected to the soil environment, STP, CP, SH, BD and pH are important factors affecting enzyme activity, and the soil environment can be enhanced by changing the planting patterns, thereby promoting an increase in aggregate nutrients and enzyme activities. To sum up, the compound planting pattern is a preferable configuration mode; it can be used as an auxiliary means of karst rocky desertification control, and has a positive role in promoting ecological environment restoration in South China Karst.

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Conflict of Interest

The authors declare no conflict of interest.

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