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KARST UNVEILED: EXPLORING THE INFLUENCE OF LAND USE ON SOIL HYDROLOGY AND NUTRIENT STATUS

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Abstract: In karst landscapes, water availability profoundly influences ecosystem management and restoration. The hydrological function of soil is pivotal in these regions, where water is often a limiting factor. Recent attention has been directed towards optimizing water and soil resources in the restoration of karst rocky desertification areas. Various factors, including land use types, management practices, and cultivation methods, exert a notable influence on soil hydrological properties. Studies, such as those by Yang and colleagues in Guangxi's Huangjiang area, have underscored the significant impact of diverse vegetation cover types on these properties. Additionally, the stoichiometric characteristics of soil carbon (C), nitrogen (N), and phosphorus (P) play a vital role in predicting soil nutrient saturation status. While extensive research has examined the ecological stoichiometry of C, N, and P in karst regions, particularly in relation to vegetation and litter, limited attention has been given to the correlation between soil hydrological properties and these key elements under different land use types. Moreover, the mechanisms governing their spatial effects remain elusive. This chapter seeks to bridge this gap by exploring these correlations, thereby furnishing a theoretical framework for comprehending the intricate soil-water-fertilizer coupling mechanism in karst regions.

Keywords: Karst landscapes, soil hydrological function, vegetation restoration, nutrient saturation, ecological stoichiometry.

Introduction

In karst landscapes, water is a limiting factor for ecosystem management and restoration, and soil hydrological function plays a crucial role in karst regions [1]. In recent years, vegetation restoration methods have become a research focus for karst rocky desertification areas, with optimizing water and soil resources being a major concern [2]. Different land use types, land management practices, and cultivation methods have a significant impact on soil hydrological properties [1]. Studies conducted by Yang [3] and others in areas such as Huangjiang in Guangxi have found significant effects of different vegetation cover types on soil hydrological properties. Additionally, soil carbon (C), nitrogen (N), and phosphorus (P) are important components of soil nutrients, and their stoichiometric characteristics can effectively predict soil nutrient saturation status [4]. There have been numerous studies on the ecological stoichiometry of C, N, and P in karst regions. For example, Yue-feng Y U [5] used a spacefor-time substitution method to study the stoichiometric characteristics of soils under different vegetation types, and some studies have shown the response of surface soil and microbial C:N:P ratios to vegetation succession [6]. Furthermore, extensive experimental research has been conducted on the stoichiometric characteristics of vegetation and litter [7]. However, there is limited research on the correlation between soil hydrological properties and soil C, N, and P under different land use types, and the mechanisms of their spatial effects remain unclear. This chapter aims to investigate this correlation and provide a theoretical foundation for understanding the soil-water-fertilizer coupling mechanism in karst regions.

1. Materials and Methods

1.1. Study Area Description

The study area is located in the northern and southern banks of the Nanpan River section, at the border of Guanling County and Zhenfeng County, Anshun City, Guizhou Province, on the Yunnan-Guizhou Plateau (105°36′30″-46′30″E, 25°39′13″-41′00″N). The elevation ranges from 450 to 1450 meters. The area has a typical tropical and subtropical monsoon humid climate. The parent material is mainly Triassic Baiyun limestone and calcareous shale, and the dominant soil types are weakly alkaline black and yellow-brown lime soils. The soil layer is shallow and not continuous.

1.2. Soil Sample Collection and Processing

Four land use types were selected on both banks of the Nanpan River: Farmland (FL), Zanthoxylum planispinum land (ZPL), Dragon fruit land (DFL), and Loquat land (LL). Within each 10 m×10 m grid, two random points were selected within a 5-meter radius from the center for soil sampling using an auger (100 cm2) to maintain soil structure. Before sampling, surface debris such as humus was removed. A total of 50 soil samples were collected for each land use type, resulting in a total of 200 samples. These samples were brought back to the laboratory for measuring bulk density (BD), maximum moisture capacity (MMC), capillary moisture capacity (CMC), soil capillary porosity (SCP), and soil total porosity (STP). Water content (WC) was determined using the oven-drying method.

Soil organic carbon was determined using the H_2SO_4-K_2CrO_4 heating method. Total carbon and total nitrogen were measured using the Vario III elemental analyzer, a German-manufactured instrument. Total phosphorus was determined by digesting the soil samples with $HClO_4$-H_2SO_4. The measurement of phosphorus in the solution was done using the molybdenum antimony anti-colorimetric method, which involves the formation of phosphomolybdenum blue, followed by quantification using a UV spectrophotometer.

1.3. Data Processing

The data were analyzed using SPSS 20.0 software for one-way analysis of variance (ANOVA), classical descriptive statistics, and normality tests. Correlation analysis was conducted using the ggplot2 and GGally packages in R 4.2.2 software.

2. Results and Analysis

2.1. Variations in Soil Hydrological Properties under Different Land Use Types

As shown in Figure 1, there were significant differences in soil hydrological properties among the four different land use types. We conducted a comprehensive analysis of the attribute differences in soil hydrological properties, including bulk density, water content, maximum moisture capacity, capillary moisture capacity, capillary porosity, and total porosity, in farmland, Zanthoxylum planispinum land, dragon fruit land, and loquat land, as shown in Figure 1. These indicators are important for evaluating soil water storage capacity and assessing soil quality, and they exhibited significant variations among different land use types. Specifically, the bulk density of the soil ranged from 0.85g·kg^{-1}~1.47g·kg^{-1}, with an average value of 1.13g·kg^{-1}. The specific order was dragon fruit land (1.36g·kg^{-1}) > Zanthoxylum planispinum land (1.09g·kg^{-1}) > loquat land (1.06g·kg^{-1}) > farmland (1.01g·kg^{-1}). One-way ANOVA results indicated that the bulk density of dragon fruit land was significantly higher than that of farmland, Zanthoxylum planispinum land, and loquat land ($p<0.05$). The bulk density of Zanthoxylum planispinum land and loquat land was significantly higher than that of farmland ($p<0.05$), while there was no significant difference in bulk density between Zanthoxylum planispinum land and loquat land ($p > 0.05$).

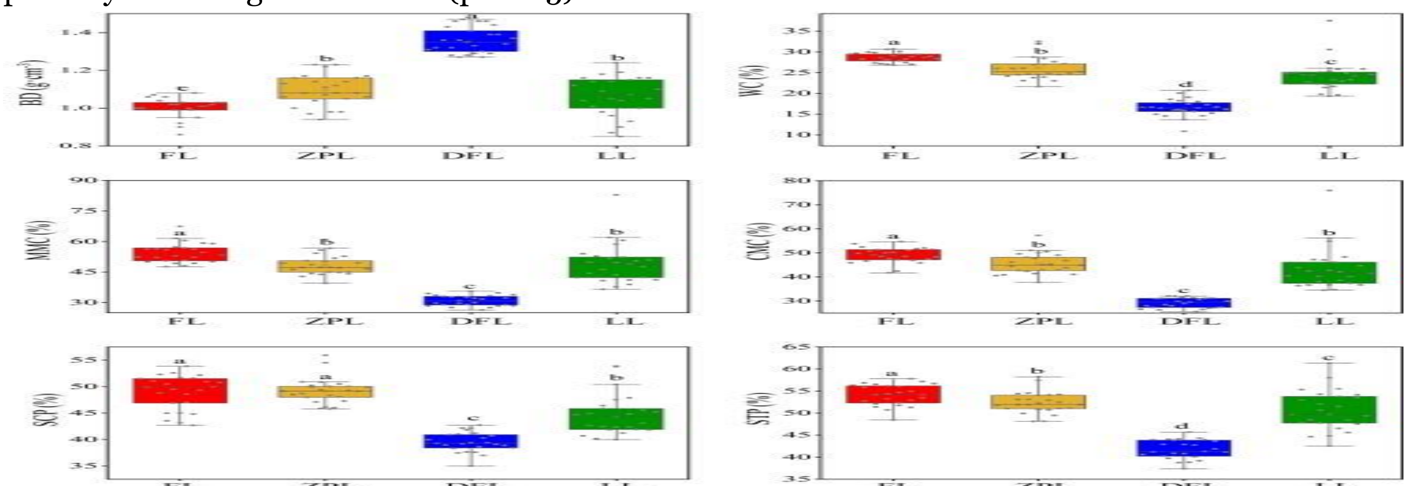
The soil moisture content ranged from 10.78% ~ 37.51%, with an average of 23.78%. Specifically, the soil moisture content (28.68%)＞the Zanthoxylum planispinum land (26.12%)＞loquat land (23.74%)＞dragon fruit land (16.56%). The one-way analysis of variance (ANOVA) results indicated that the soil moisture content in farmland was significantly higher than that in Zanthoxylum planispinum land, dragon fruit land, and loquat land ($p<0.05$). The soil moisture content in Zanthoxylum planispinum land was significantly higher than that in loquat land and dragon fruit land ($p<0.05$), and the soil moisture content in loquat land was significantly higher than that in dragon fruit land ($p<0.05$).

The overall range of soil maximum moisture capacity varied from 30.94% ~ 54.40%, with an average of 45.72%. The specific rankings were as follows: farmland (54.40%) > loquat land (49.09%) > Zanthoxylum planispinum land (48.46%) > dragon fruit land (30.94%). One-way ANOVA results showed that the maximum moisture capacity of farmland was significantly higher than that of Zanthoxylum planispinum land, dragon fruit land, and loquat land ($p<0.05$). Both Zanthoxylum planispinum land and loquat land had significantly higher maximum moisture capacity than dragon fruit land ($p<0.05$), while there was no significant difference between Zanthoxylum planispinum land and loquat land ($p>0.05$).

The overall range of soil capillary moisture capacity varied from 29.22% ~ 49.02%, with an average of 41.77%. The specific rankings were as follows: farmland (49.02%) > Zanthoxylum planispinum land (45.50%) > loquat land (43.34%) > dragon fruit land (29.22%). One-way ANOVA results showed that the capillary moisture capacity of farmland was significantly higher than that of Zanthoxylum planispinum land, dragon fruit land, and loquat land ($p<0.05$). Zanthoxylum planispinum land and loquat land exhibited significantly higher capillary moisture capacity than dragon fruit land ($p<0.05$), while no significant difference was found between Zanthoxylum planispinum land and loquat land ($p>0.05$).

The overall range of soil capillary porosity varied from 39.49% ~ 49.18%, with an average of 45.56%. The specific rankings were as follows: Zanthoxylum planispinum land (49.18%) > farmland (48.93%) > loquat land (44.64%) > dragon fruit land (39.49%). One-way ANOVA results showed that both farmland and Zanthoxylum planispinum land had significantly higher capillary porosity than dragon fruit land and loquat land ($p<0.05$). Furthermore, loquat land exhibited significantly higher capillary porosity than dragon fruit land ($p<0.05$), while no significant difference was observed between farmland and Zanthoxylum planispinum land ($p>0.05$).

The overall range of soil total porosity varied from 41.76% ~ 54.08%, with an average of 49.70%. The specific rankings were as follows: farmland (54.08%) > Zanthoxylum planispinum land (52.34%) > loquat land (50.63%) > dragon fruit land (41.76%). One-way ANOVA results showed that the total porosity of farmland was significantly higher than that of Zanthoxylum planispinum land, dragon fruit land, and loquat land ($p<0.05$). Zanthoxylum planispinum land had significantly higher total porosity than dragon fruit land and loquat land ($p<0.05$), while loquat land exhibited significantly higher total porosity than dragon fruit land ($p<0.05$).



Note: Different lowercase letters indicate significant differences between land use types ($p<0.05$).
Figure 1: Comparison of soil hydrological properties under different land use patterns.

2.2. Differences in Soil C: N: P Stoichiometry among Different Land Uses

Significant differences were observed in soil C, N, and P stoichiometry among the four different land uses. A comprehensive analysis of the differences in soil C, N, and P stoichiometry among farmland, Zanthoxylum planispinum land, dragon fruit land, and loquat land is shown in Figure 2. Soil C, N, and P content, as well as their stoichiometric ratios, are important factors for evaluating soil quality and play a crucial role in organic matter composition and biogeochemical cycles.The soil organic carbon (SOC) content ranged from 7.40$g\cdot kg^{-1}$~73.43$g\cdot kg^{-1}$, with an average of 31.49$g\cdot kg^{-1}$. Specifically, the rankings were as follows: farmland (47.34$g\cdot kg^{-1}$) > Zanthoxylum planispinum land (33.62$g\cdot kg^{-1}$) > loquat land (31.11$g\cdot kg^{-1}$) > dragon fruit land (13.89$g\cdot kg^{-1}$). One-way ANOVA results indicated that the SOC content in farmland was significantly higher than that in Zanthoxylum planispinum land, dragon fruit land, and loquat land ($p<0.05$). The SOC content in Zanthoxylum planispinum land and loquat land was significantly higher than that in dragon fruit land ($p<0.05$), but there was no significant difference between Zanthoxylum planispinum land and loquat land ($p > 0.05$).

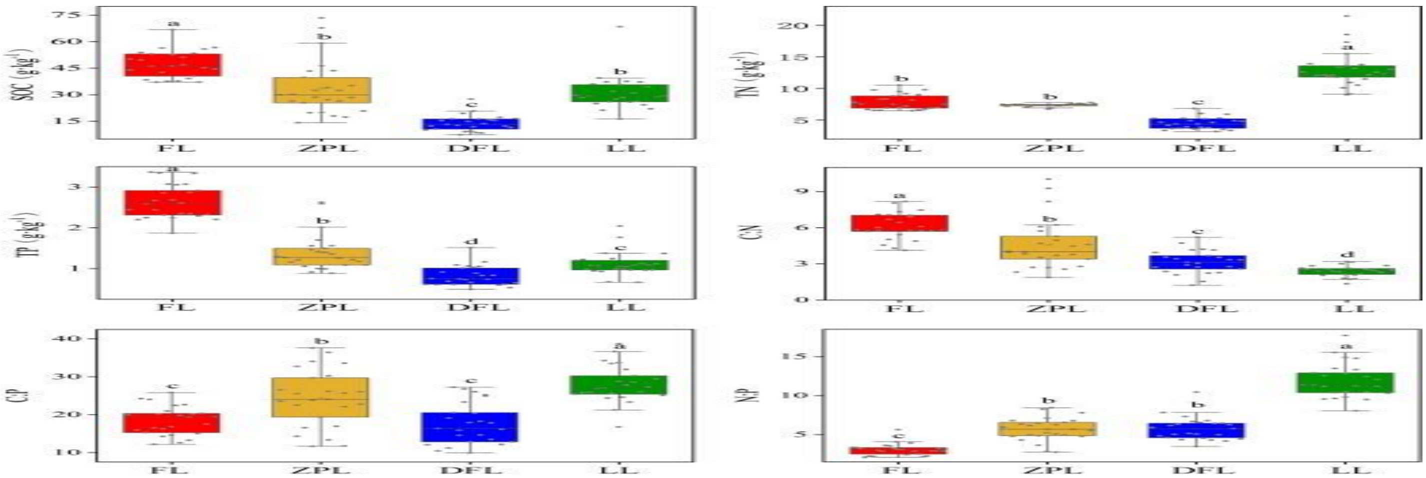
Soil total nitrogen (TN) exhibited a range of 3.18$g\cdot kg^{-1}$~21.46$g\cdot kg^{-1}$, with an average of 8.16$g\cdot kg^{-1}$. The specific rankings were as follows: loquat land (12.97$g\cdot kg^{-1}$) > farmland (7.84$g\cdot kg^{-1}$)> Zanthoxylum planispinum land ($7.33g·kg^{-1}$) > dragon fruit land ($4.50g·kg^{-1}$). One-way ANOVA results indicated that TN content in loquat land was significantly higher than that in farmland, Zanthoxylum planispinum land, and dragon fruit land ($p<0.05$). TN content in farmland and Zanthoxylum planispinum land was significantly higher than that in dragon fruit land ($p<0.05$), while no significant difference was observed between farmland and Zanthoxylum planispinum land ($p > 0.05$).

Soil total phosphorus (TP) exhibited a range of $0.49g·kg^{-1}$~$3.37g·kg^{-1}$, with an average of $5.96g·kg^{-1}$. The specific rankings were as follows: farmland ($2.63g·kg^{-1}$) > Zanthoxylum planispinum land ($1.39g·kg^{-1}$)> loquat land ($1.12g·kg^{-1}$) > dragon fruit land ($0.82g·kg^{-1}$). One-way ANOVA results indicated that TP content in farmland was significantly higher than that in the other three land types ($p<0.05$). TP content in Zanthoxylum planispinum land was significantly higher than that in dragon fruit land and loquat land ($p<0.05$), while TP content in loquat land was significantly higher than that in dragon fruit land ($p<0.05$).

The soil C: N ratio exhibited a range of 1.23 ~ 10.03, with an average of 4.07. The specific rankings were as follows: farmland (6.12) > Zanthoxylum planispinum land (4.59) > dragon fruit land (3.16) > loquat land (2.40). One-way ANOVA results indicated that the C: N ratio in farmland was significantly higher than that in the other three land types ($p<0.05$). The C: N ratio in Zanthoxylum planispinum land was significantly higher than that in dragon fruit land and loquat land ($p<0.05$), while the C: N ratio in dragon fruit land was significantly higher than that in loquat land ($p<0.05$).

The soil C: P ratio exhibited a range of 9.91 ~ 38.72, with an average of 22.06. The specific rankings were as follows: loquat land (27.97) > Zanthoxylum planispinum land (24.28) > farmland (18.38) > dragon fruit land (17.61). One-way ANOVA results indicated that the C: P ratio in loquat land was significantly higher than that in the other three land types ($p<0.05$). The C: P ratio in Zanthoxylum planispinum land was significantly higher than that in farmland and dragon fruit land ($p<0.05$), while no significant difference was observed between farmland and dragon fruit land ($p > 0.05$).

The soil N: P ratio exhibited a range of 2.09 ~ 17.71, with an average of 6.60. The specific rankings were as follows: loquat land (11.88) > dragon fruit land (5.75) > Zanthoxylum planispinum land (5.69) > farmland (3.06). One-way ANOVA results indicated that the N: P ratio in loquat land was significantly higher than that in the other three land types ($p<0.05$). The N: P ratio in dragon fruit land and Zanthoxylum planispinum land was significantly higher than that in farmland ($p<0.05$), while no significant difference was observed between dragon fruit land and Zanthoxylum planispinum land ($p > 0.05$).



Note: Different lowercase letters indicate significant differences between land use types (p<0.05).
Figure 2: Comparison of soil C: N: P stoichiometric characteristics under different land use types.

3. Discussion

This study demonstrates significant differences in soil bulk density, moisture content, maximum water-holding capacity, capillary water-holding capacity, capillary porosity, and total porosity among the four different land use types. The comprehensive analysis shown in Figure 1 reveals that the soil bulk density is highest in the dragon fruit plantation, followed by cultivated land, pepper forest land, and loquat forest land in descending order. Low bulk density is crucial for water availability, soil aggregate composition, and nutrient cycling [8,9]. The high bulk density observed in the dragon fruit plantation is consistent with the findings of Yi et al. [10] in their study on dragon fruit cultivation sites. This might be attributed to the cultivation practices and planting history of the dragon fruit plantation. Additionally, the dragon fruit plantation shows the lowest values for the remaining five variables, and the correlation analysis in Figure 2 indicates a negative relationship between soil bulk density and the other five variables. Both cultivated land and pepper forest land exhibit significantly lower soil bulk density than the dragon fruit plantation ($p<0.05$), while they demonstrate significantly higher values for moisture content, maximum water-holding capacity, capillary water-holding capacity, and total porosity compared to the dragon fruit plantation ($p<0.05$). This could be due to the influence of root growth and human disturbance on cultivated land, leading to a looser soil structure. Furthermore, studies by Nie et al. [11] have shown that tree roots in the shallow soil environment of the southwestern karst region become finer and extend horizontally. Therefore, the surface soil structure and hydrological properties are better in pepper forest land and loquat forest land. The cultivated land soil, on the other hand, may have a loose soil structure due to long-term human tillage, resulting in lower surface soil bulk density and increased moisture content, water-holding capacity, and porosity during the sampling period in April.

Correlation analysis in Figures 3-6 reveals significant positive relationships between soil organic carbon (SOC) and moisture content in cultivated land, dragon fruit plantation, and loquat forest land. This finding is consistent with the results of Song et al. [6], who found that soils with higher moisture content generally have higher organic carbon. This could be attributed to soil organic carbon as an

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important component of organic matter, which can improve soil structure, increase soil aggregate porosity, and subsequently enhance soil permeability and water infiltration rates [12]. Additionally, Zhang et al. [13] demonstrated that the unique karst processes in the karst region result in the exposure of a large number of rocks on slopes, forming unique microhabitats such as rock fissures, gullies, and crevices. The soils extensively developed in these microhabitats are known as surface karst fissure fill soils (EFS), which are important influencing factors controlling karst hydrological processes and eco-hydrological functions [14]. Precipitation infiltrates through the surrounding rocks into the EFS, redistributing water and carrying a significant amount of nutrient and mineral elements from the rock surface into the soil. This process is particularly prominent in areas with dense natural vegetation such as pepper forest land and loquat forest land, where the degree of human disturbance is reduced due to reforestation efforts. As a result, these areas exhibit strong soil water and nutrient supply capacity. Consequently, pepper forest land and loquat forest land have lower soil bulk density, better pore structure, higher soil moisture content, maximum water-holding capacity, and capillary water-holding capacity. The relatively lower soil structure in the loquat forest land compared to pepper forest land may be due to the construction of terraced fields, which, although enhancing soil conservation benefits [15], reduces surface runoff and consequently lowers the erosion of surface rocks and soil by precipitation [16].

Figure 2 in this study shows that in cultivated land, the soil C:P ratio is greater than the C:N ratio, which is greater than the N:P ratio. However, in pepper forest land, dragon fruit plantation, and loquat forest land, the pattern is C:P ratio greater than N:P ratio, which is greater than the C:N ratio. The soil N:P ratio serves as a threshold for determining nitrogen and phosphorus limitations in soils [17], with a smaller N:P ratio indicating a more severe nitrogen limitation [18]. Research has shown that the average soil N:P ratio in typical rocky desertification systems in the southwest karst region is 3.45 [19]. In this study, except for the N:P ratio of 3.06 in cultivated land, the N:P ratios in pepper forest land, dragon fruit plantation, and loquat forest land are 5.69, 5.75, and 11.88, respectively, all higher than 3.45. This indicates that compared to the southwest karst system, nitrogen is relatively deficient and becomes a limiting factor for soil nutrients in cultivated land, while phosphorus is the limiting factor in the other three land types. Li et al. [20] pointed out that the reason for the low soil C:N ratio in pepper forest land is that the mineralization rate of carbon is higher than that of nitrogen, combined with insufficient nitrogen supplementation through artificial fertilization, resulting in a low C:N ratio. Additionally, Qu et al. [21] observed phosphorus deficiency during the cultivation of pepper forest land.

This finding is consistent with the results of many other studies [22-24]. In many terrestrial ecosystems, sustained nitrogen accumulation can lead to a transition from nitrogen limitation to dual nitrogen and phosphorus limitation, or even phosphorus limitation. This transition is related to changes in vegetation cover under different land use types, as different plant species undergo this shift when they absorb large amounts of phosphorus [25].

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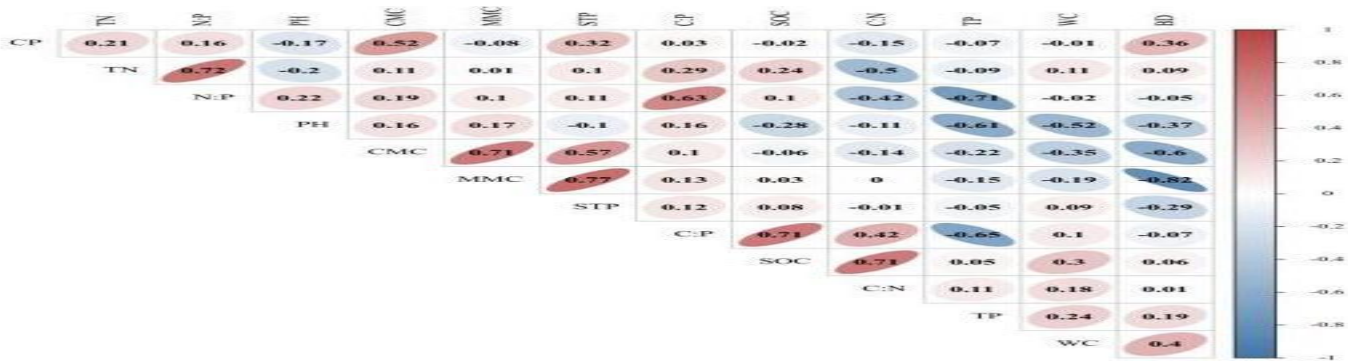

Figure 3: Correlation analysis between soil hydrological properties and C: N: P stoichiometric characteristics of farmland.

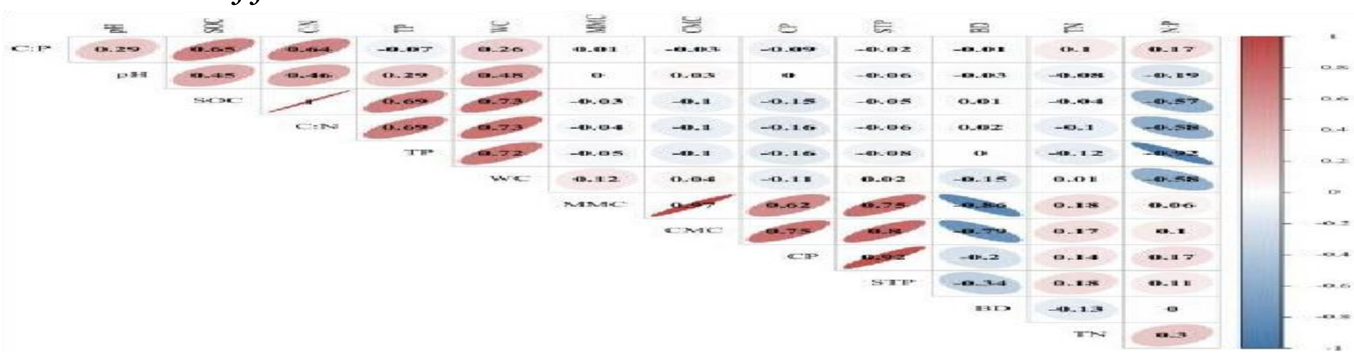

Figure 4: Correlation analysis between soil hydrological properties and C: N: P stoichiometric characteristics in Zanthoxylum planispinum land

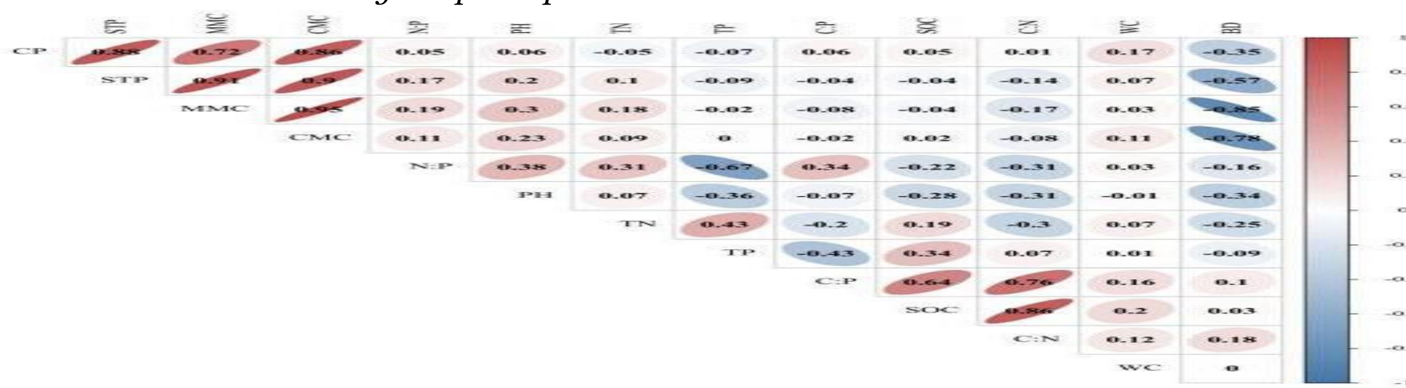

Figure 5: Correlation analysis between soil hydrological properties and C: N: P stoichiometric characteristics in dragon fruit field.

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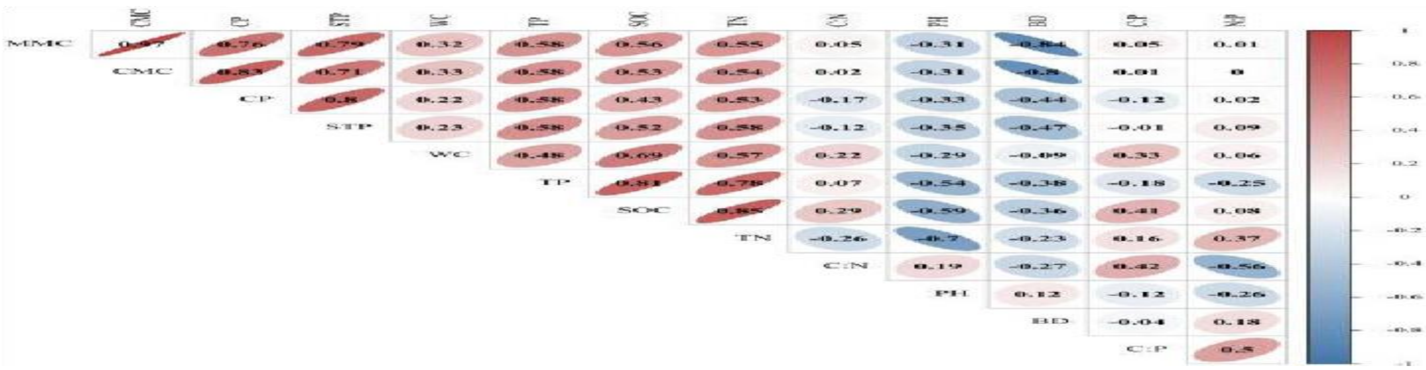

Figure 6: Correlation analysis between soil hydrological properties and C: N: P stoichiometric characteristics in loquat land.

4. Conclusion

(1) There are significant differences in soil hydrological properties among the four different land use types. The soil hydrological properties in the dragon fruit plantation are significantly lower than those in the cropland, pepper forest, and loquat forest ($p<0.05$). However, the bulk density is significantly higher in the dragon fruit plantation compared to the other three land use types, indicating poorer soil structure. The cropland exhibits the best soil hydrological properties among the four land use types. Correlation analysis indicates a significant positive relationship between soil organic carbon (SOC) and soil moisture content for all four land use types.

(2) There are significant differences in soil C, N, and P stoichiometric characteristics among the four different land use types. The cropland has the highest SOC and total phosphorus (TP) content, while the loquat forest has the highest total nitrogen (TN) content. The N:P ratio in the cropland is lower than the average value in the typical karst rocky desertification system of southwestern China, indicating that nitrogen deficiency is the main limiting factor for soil fertility. On the other hand, phosphorus deficiency is the main limiting factor for soil fertility in the pepper forest, dragon fruit plantation, and loquat forest. Therefore, based on the findings of this study, it can be concluded that different land use types significantly influence soil hydrological properties and C, N, and P stoichiometric characteristics. These findings contribute to our understanding of the impacts of land use on soil quality and provide insights for sustainable land management and agricultural practices.

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