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Soil Properties of Different Planting Combinations of *Zanthoxylum planispinum* var. *dintanensis* Plantations and Their Effect on Stoichiometry

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Abstract: The soil quality of plantations with different planting patterns and the effect of soil quality on stoichiometry provide a theoretical basis for the selection of *Zanthoxylum planispinum* var. *dintanensis* (hereafter *Z. planispinum*) planting patterns and nutrient management. Four mixed plantations: *Z. planispinum* + *Prunus salicina*, *Z. planispinum* + *Sophora tonkinensis*, *Z. planispinum* + *Arachis hypogaea*, and *Z. planispinum* + *Lonicera japonica*, and a monoculture *Z. planispinum* plantation were selected to clarify the effect of soil quality on stoichiometry. The results showed that the soil quality index (SQI) of *Z. planispinum* + *L. japonica* (1.678) was the highest, indicating that it was the preferred planting combination and that it was significantly limited by soil water content (SWC). The nutrient forms, SWC, and pH all have significant effects on processes such as nutrient transformation and cycling. The contributions of total Ca and total Mg in soil nutrients to stoichiometry were relatively high, while the effect of SQI on stoichiometry was not significant. The microbial stoichiometry ratio was mainly influenced by microbial biomass phosphorus, reflecting that microorganisms have strong internal stability. Strong interactions among soil factors occur, affecting elemental geochemical processes. The regulatory effects of different soil factors on their stoichiometry should be emphasized.

Keywords: *Zanthoxylum planispinum* var. *dintanensis*; planting combination; soil quality; stoichiometry

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1. Introduction

The deciduous shrub *Zanthoxylum planispinum* var. *dintanensis* (hereafter *Z. planispinum*) has the advantages of fragrance and numbing taste, calcium (Ca) preference, drought tolerance, and easy management [1]. Because it is suitable for a dry and hot karst climate and Ca-rich soil, it has become the main planting species in Guizhou Province, with both ecological and economic benefits [2]. Plantations of *Z. planispinum* are mainly monocultures, and it has been confirmed that continuous monoculture planting can easily lead to the decline of soil fertility and productivity [3]. It has been shown that scientific plant combinations can effectively improve biodiversity and change nutrient delivery to the soil by changing the quantity and quality of litter and root secretions [4,5]. Ecological stoichiometry is the science that unifies different ecological levels to study the interaction of energy and multiple elements in ecosystems and is an important method for diagnosing nutrient limitation and balance [6]. There is a strong link between the physical properties, pH, and nutrient elements of soils, the relative components of which can drive the microbial community to secrete extracellular enzymes to obtain limiting nutrients from the soil, ultimately changing the soil ecological stoichiometric ratio [7]. Since soil quality influences soil stoichiometry, studying their intrinsic relationship can help to accurately quantify soil quality in both content and stoichiometric dimensions [8]. Therefore, combining ecological stoichiometry to explore the effects of plant combinations on soil quality and dissecting soil nutrient balance mechanisms can provide a theoretical basis for soil nutrient diagnosis of composite plantings and serve the selection and breeding of *Z. planispinum* plantations in karst.

Companion planting is an organic combination of various plants based on the physiological and ecological characteristics of different species, with the aim of improving the biodiversity of the community and promoting soil nutrient cycling. Researchers have chosen simple, sensitive, and representative indicators to assess the impact of planting patterns on soil quality. Stocker et al. [9] found that an agroforestry system in southern Brazil improved physical properties such as soil bulk density and total porosity. Ma et al. [10] elucidated that intercropping of Chinese chestnut trees (*Castanea mollissima)* with tea (*Camellia sinensis*) in temperate regions of China increased soil organic matter, nitrogen (N), phosphorus (P), and potassium (K) content as well as enzyme activity. Zhou et al. [11] concluded that the Chinese fir (*Cunninghamia lanceolata*) mix produced some improvement in soil quality, especially soil chemical properties, providing preliminary data for further research on the effect of tree species combination proportions on soil properties. *Z. planispinum* interplanting largely increased the content of trace elements in the soil and improved soil fertility [12]. Therefore, the scientific combination of species is conducive to improving soil fertility, the stability of forest stands, and ecological functions [13]. However, previous studies have focused on soil physicochemical indicators, with less attention paid to microorganisms [14], and the Ca and magnesium (Mg) in karst areas have rarely been addressed [15,16]. In addition, vegetation type affects soil quality, which in turn changes stoichiometry, but there are fewer reports on the relationship between soil quality and stoichiometry in mixed *Z. planispinum* forests [17,18]. Therefore, studying the soil quality of *Z. planispinum* plantations with different companion plants and its driving effect on stoichiometry can reveal the nutrient limitation status from the microscopic perspective of soil components and screen for more stable vegetation types.

Soil water content (SWC) and temperature (ST) are easy to measure as physical indicators and have direct and indirect effects on nutrient cycling. Carbon (C), N, P, and K are important biogenic elements in the soil. *Z. planispinum* is a Ca preference plant, so Ca plays a regulatory role in plant growth and development, while Ca and Mg are characteristic elements with high content in karst areas. Microbial concentration, biomass, and extracellular enzyme activity are sensitive to chemical reactions and play an important role in the nutrient cycling process. Based on this, we comprehensively studied the soil quality and its intrinsic correlation with stoichiometry in different planting patterns of *Z. planispinum* through soil physical and chemical properties, as well as microbial concentration, biomass C, N, P, and extracellular enzyme activity measurements. We aimed to analyze the extent to which soil physical, chemical, and biological properties affect the overall soil quality and identify important indicators for evaluating soil fertility. In addition, we intended to dissect the changes in the pattern of soil quality with planting pattern and to clarify the driving effect of soil quality on stoichiometry. Theoretically, we clarified the influence of species combinations on soil quality and revealed the driving mechanism of soil quality on stoichiometry; in practice, the best species combination was selected to improve the stability and ecological function of a plantation.

2. Materials and Methods

2.1. Overview of the Research Site

The study area is located in Beipanjiang Town, Guizhou Province, China (105°38′35″ E, 25°39′37″ N), with a typical river valley topography, 530–1473 m above sea level. On a long-term scale, the climate type is mainly subtropical humid monsoon climate. The region is rich in heat resources, with an average annual temperature of 18.4 °C and a total annual accumulated temperature of 6542.9 °C. The seasonal distribution of rainfall is uneven, with an average annual rainfall of 1100 mm and severe droughts in winter and spring. The site has serious rock desertification. The soil type mainly consists of limestone and marl as the parent material of soil formation with the exposed area of bedrock exceeding 70% [19]. Soil pH value is >6.5, and the soil exchangeable Ca and Mg content is high. The sampling year was 2020, in which the average temperature was 16.5 °C, the maximum and minimum temperatures were 36.0 and 0.0 °C, respectively, and the total annual accumulated temperature reached 5998.4 °C, with an annual precipitation of 1221.1 mm. Based on previous research results, we ascertained that the regional soil organic carbon, total N, fast-acting N, total P, and fast-acting P contents were in the order of 26.16, 4.58, 0.77, 1.62, and 0.01 g·kg^{-1}.

Since 1992, the area of *Z. planispinum* cultivation has been gradually extended in the dry and hot karst valley area of Guizhou Province and now covers more than 10,000 ha. The yield of *Z. planispinum* is 4–5 kg·plant^{-1} and 4800 kg·ha^{-1}. The output value reached RMB 120 million in 2007 and currently exceeds RMB 700 million (data not publicly available). Because of its excellent quality traits, it has become a protected geographical indication product and has been given a geographical indication certification trademark. Due to the development of stone desertification, a "stitch-and-shoot" planting method was adopted. In order to increase biodiversity and ecosystem stability, and to improve land use efficiency for economic gain, a number of composite planting patterns have gradually emerged [20]. However, due to the complexity of interspecific relationships, there is an urgent need to carry out research into planting pattern preferences.

2.2. Sample Plot Setting

Four common planting combinations were selected, namely, *Z. planispinum* + *Prunus salicina*, *Z. planispinum* + *Sophora tonkinensis*, *Z. planispinum* + *Arachis hypogaea*, and *Z. planispinum* + *Lonicera japonica*. A monoculture stand of *Z. planispinum* plantation was used as a control. One sample plot with similar environmental factors was set up for each of the five selected plantations. The *Z. planispinum* used in all five plantations was guaranteed to be of the same age, and the survey factors of the sample plots are shown in Table 1. At 5 years after planting *Z. planispinum*, *Prunus salicina*, *Sophora tonkinensis*, *Arachis hypogaea*, and *Lonicera japonica* were planted around them and grown for a further 3 years. The planting density was 600–750, 1500–1800, 2500, or 450–600 plants/ha. Before planting *Z. planispinum*, all the plots had been mainly planted with maize (*Zea mays*) and had the same management level and thus can be regarded as having similar soil fertility in space. The sample plots were set up with more consistent management measures such as shaping and pruning and fertilization to avoid affecting soil biology and to control the homogeneity of experimental results. The detailed management measures used for the five plantation species were as described previously [21], based on discussion of the effects of the species combinations on soil elements, microorganisms, and extracellular enzymes as a continuum, and the intrinsic interconnections between the three, to explore the effect of the plant combinations on soil quality, and its effect on stoichiometry by analyzing single soil factors and composite indices.

Table 1. General information of plots.

Plantation Type	Species Combinations	Longitude	Latitude	Growing Area (ha)	Altitude (m asl)	Density (m)	Height (m)	Crown Width (m)	Coverage (%)
Plot 1	*Z. planispinum* + *P. salicina*	105°40′28.33″ E	25°37′57.41″ N	1.34	764	3 × 3	3.5	2 × 2.3	70
Plot 2	*Z. planispinum* + *S. tonkinensis*	105°40′19.79″ E	25°39′25.75″ N	0.67	728	2 × 2	2.0	1.2 × 1.8	60
Plot 3	*Z. planispinum* + *A. hypogaea*	105°38′36.32″ E	25°39′23.64″ N	0.67	791	2 × 2	2.5	2.5 × 2.8	85
Plot 4	*Z. planispinum* + *L. japonica*	105°38′36.35″ E	25°39′22.29″ N	6.67	814	3.5 × 3	2.5	1.5 × 2.5	70
Plot 5	*Z. planispinum*	105°38′35.64″ E	25°39′23.35″ N	33.35	788	3 × 4	2.2	2.5 × 2.3	65

2.3. Soil Sample Collection

Soil samples were collected between 19 and 21 November 2020. The average values of meteorological data during the period were: sunshine hours 6.3 h, average temperature 14.3 °C, precipitation 0 mm, evaporation 0.5 mm, and wind speed 1.2 m·s^{-1}. At this time of year, the material exchange between plants and soil is weak and the soil material composition is relatively stable. This facilitates better evaluation of the effect of the planting combination on soil quality. Sunny weather for more than 15 days prior to sampling ensured a low level of soil variability and a smaller number of tests to characterize the levels under prolonged drought conditions. Three 10 m × 10 m sample squares (with sufficient buffer strips between squares) were set up in each sample plot. Multiple sampling points were laid along S-shaped lines in the sample squares, and at each sample point equal amounts of soil from 0–10 and 10–20 cm soil layers (less than 20 cm to the actual depth), mixed evenly, were collected. Because of the shallow soil layer in karst areas, the thickness of the soil layer was mainly less than 20 cm, which is also the concentrated distribution area of fibrous roots. Therefore, only soil samples within the top 20 cm were collected in this study. Fertilization areas of 10–30 cm around the tree trunks were avoided as much as possible during sampling to minimize human interference. A total of 30 soil samples, each of about 500 g, were collected, and the fresh soil samples were divided into two parts after removing gravel (mass ratio about 15–20%), plant roots, and plant and animal residues. One part was passed through a 2 mm sieve and stored at 4 °C to determine the microbial concentration, biomass, and extracellular enzyme activity as soon as possible. The other part was air-dried and ground through a 0.15 mm sieve to determine the soil nutrient content. The determinations were completed within 7 and 30 days, respectively, after sample collection.

2.4. Index Analysis Methods

SWC and ST were measured with a TR-6 soil temperature and humidity meter. The pH value was determined by the potentiometric method [22]; available N by the alkaline diffusion method; available P by the HCl-H_2SO_4 leaching method; available K by flame photometry; and the contents of available Ca and available Mg were determined by atomic absorption spectrophotometry [23]. Soil total nutrients and microbial properties were determined as described by Li et al. [21], with the following data (Tables 2 and 3).

Table 2. Soil total nutrients of *Z. planispinum* plantation in different planting combinations.

Soil Parameters	Soil Depth (cm)	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5
Soil organic carbon	0–10	36.05 ± 9.83 Aab	32.45 ± 2.05 Aab	28.75 ± 15.49 Ab	59.55 ± 16.48 Aa	27.05 ± 1.34 Ab
($g{\cdot}kg^{-1}$)	10–20	39.40 ± 4.81 Aa	26.35 ± 0.92 Aa	27.60 ± 12.59 Aa	42.10 ± 10.18 Aa	25.95 ± 3.04 Aa
Total nitrogen	0–10	36.05 ± 9.83 Aab	2.78 ± 0.04 Ab	2.79 ± 0.93 Ab	5.07 ± 0.25 Aa	2.84 ± 0.23 Ab
($g{\cdot}kg^{-1}$)	10–20	39.40 ± 4.81 Aa	2.51 ± 0.11 Ab	2.78 ± 0.56 Ab	4.13 ± 0.64 Aa	2.69 ± 0.23 Ab
Total phosphorus	0–10	1.46 ± 0.13 Aab	0.99 ± 0.21 Ab	1.17 ± 0.52 Aab	1.73 ± 0.20 Aa	1.32 ± 0.01 Aab
($g{\cdot}kg^{-1}$)	10–20	1.27 ± 0.08 Aa	0.66 ± 0.13 Ab	1.04 ± 0.35 Aab	1.32 ± 0.15 Aa	1.21 ± 0.06 Aa
Total potassium	0–10	7.15 ± 0.35 Ab	6.64 ± 2.79 Ab	11.65 ± 0.78 Aa	11.65 ± 0.50 Aa	11.80 ± 0.57 Aa
($g{\cdot}kg^{-1}$)	10–20	6.75 ± 1.04 Ac	5.58 ± 0.23 Ac	13.00 ± 0.28 Aa	12.10 ± 0.57 Aa	9.96 ± 0.62 Ab
Total calcium	0–10	1.20 ± 0.85 Aa	2.35 ± 2.05 Aa	6.05 ± 6.72 Aa	1.65 ± 0.21 Aa	9.40 ± 5.37 Aa
($g{\cdot}kg^{-1}$)	10–20	1.25 ± 0.50 Ab	1.95 ± 1.34 Ab	4.65 ± 4.60 Aab	2.10 ± 0.57 Ab	8.90 ± 2.97 Aa
Total magnesium	0–10	5.30 ± 2.55 Ab	5.65 ± 3.32 Ab	7.85 ± 1.91 Ab	8.45 ± 1.06 Ab	15.45 ± 0.21 Aa
($g{\cdot}kg^{-1}$)	10–20	5.10 ± 0.57 Ab	4.25 ± 0.21 Ab	11.45 ± 4.88 Aa	8.75 ± 1.20 Aab	12.25 ± 2.05 Aa

Plot 1, *Z. planispinum* + *P. salicina*; plot 2, *Z. planispinum* + *S. tonkinensis*; plot 3, *Z. planispinum* + *A. hypogaea*; plot 4, *Z. planispinum* + *L. japonica*; plot 5, *Z. planispinum* monoculture plantation. Lower case letters indicate significant differences between different plantation types of the same depth at $p < 0.05$; upper case letters indicate significant differences between different depths of the same plantation types at $p < 0.05$. One-way ANOVA was used to calculate the differences, $p = 0.05$, n = 15. Data are presented as mean ± standard deviation.

2.5. Data Processing

The stoichiometry was calculated with reference to Sinsabaugh et al. [24] Microsoft Excel 2013 (version 2013, Microsoft, Redmond, WA, USA) was used to pre-process the data. One-way analysis of variance (ANOVA) at 95% confidence level was performed using SPSS 20.0 (version 20.0, IBM SPSS, Armonk, NY, USA) to test the variability of soil physicochemical properties. The mean values were separated by using the least significance difference test (LSD) in all cases [25,26]. Principal component analysis (PCA) was used to comprehensively evaluate the soil quality index (SQI) of the *Z. planispinum* plantation ecosystem with different planting combinations, and the indicators were standardized and pre-treated before evaluation. The weighted method was used to calculate the SQI, with the expression [27]:

$$SQI = \Sigma W_i \times F_{\rm i}$$

where W_i is the contribution rate of each principal component, and F_i is the principal component score of each planting combination. Weighting the variance contribution rate (W_i) and factor score (F_i) of each principal component factor, the SQI of different planting combinations was obtained.

Table 3. Soil microbial concentration, biomass, and extracellular enzyme activity of *Z. planispinum* plantation in different planting combinations.

Soil Parameters	Soil Depth (cm)	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5
Fungal concentration	0–10	11.75 ± 4.60 Aa	11.00 ± 1.41 Aa	9.60 ± 4.81 Aa	12.00 ± 1.41 Aa	8.40 ± 2.26 Aa
($\times 10^3$ CFU·g^{-1})	10–20	12.50 ± 3.54 Aa	9.00 ± 2.83 Aa	5.95 ± 0.21 Aa	12.20 ± 5.37 Aa	7.45 ± 3.61 Aa
Bacterial concentration	0–10	2.35 ± 0.09 Abc	5.30 ± 0.71 Aa	3.00 ± 0.99 Abc	3.15 ± 0.49 Ab	1.20 ± 0.00 Ac
($\times 10^6$ CFU·g^{-1})	10–20	4.85 ± 1.06 Aa	1.80 ± 0.42 Bbc	2.20 ± 1.56 Aabc	4.40 ± 1.13 Aab	1.55 ± 0.78 Ac
Actinomycete concentration	0–10	21.50 ± 12.02 Aa	26.50 ± 0.71 Aa	14.65 ± 6.15 Aa	25.00 ± 7.07 Aa	9.30 ± 0.57 Aa
($\times 10^5$ CFU·g^{-1})	10–20	26.50 ± 13.44 Aa	9.95 ± 0.07 Ba	15.00 ± 7.07 Aa	32.15 ± 11.10 Aa	10.10 ± 5.52 Aa
Microbial biomass carbon	0–10	265.00 ± 15.56 Aa	252.00 ± 8.49 Aa	249.50 ± 20.51 Aa	245.00 ± 19.80 Aa	262.00 ± 9.90 Aa
(mg·kg^{-1})	10–20	221.00 ± 5.66 Ab	257.50 ± 3.54 Aab	254.50 ± 14.85 Aab	280.50 ± 23.33 Aa	262.50 ± 43.13 Aab
Microbial biomass nitrogen	0–10	12.75 ± 3.18 Aa	14.90 ± 1.27 Aa	15.65 ± 0.35 Aa	13.70 ± 0.42 Aa	13.30 ± 1.56 Aa
(mg·kg^{-1})	10–20	12.05 ± 0.21 Aa	12.25 ± 1.34 Aa	13.10 ± 1.56 Aa	14.10 ± 1.70 Aa	14.85 ± 1.91 Aa
Microbial biomass phosphorus	0–10	120.00 ± 21.21 Ab	150.00 ± 5.66 Aab	152.00 ± 14.14 Aab	161.00 ± 9.90 Aa	126.00 ± 11.31 Ab
(mg·kg^{-1})	10–20	136.00 ± 25.46 Aa	139.00 ± 4.24 Aa	144.00 ± 2.83 Aa	148.00 ± 16.97 Aa	152.00 ± 4.24 Aa
β-1,4-glucosidase	0–10	6.38 ± 0.03 Aa	6.24 ± 0.33 Aa	6.49 ± 0.32 Aa	6.38 ± 0.74 Aa	6.28 ± 0.74 Aa
[μmol·(min·g)$^{-1}$]	10–20	5.67 ± 0.02 Bb	6.05 ± 0.17 Ab	6.18 ± 0.28 Ab	6.96 ± 0.02 Aa	6.30 ± 0.45 Ab
β-1,4-N-acetylglucosaminidase	0–10	35.39 ± 0.17 Aa	34.41 ± 2.25 Aa	36.12 ± 2.25 Aa	35.39 ± 5.19 Aa	34.66 ± 5.20 Aa
[μmol·(min·g)$^{-1}$]	10–20	30.37 ± 0.17 Bb	33.07 ± 1.21 Ab	33.98 ± 1.99 Ab	39.43 ± 0.18 Aa	34.78 ± 3.12 Ab
Leucine aminopeptidase	0–10	30.14 ± 0.12 Aa	29.47 ± 1.55 Aa	30.64 ± 1.54 Aa	30.14 ± 3.56 Aa	34.63 ± 3.51 Aa
[μmol·(min·g)$^{-1}$]	10–20	26.70 ± 0.12 Bb	28.54 ± 0.83 Ab	29.18 ± 1.36 Ab	32.91 ± 0.12 Aa	29.72 ± 2.14 Ab
Acid phosphatase	0–10	7.51 ± 0.03 Aa	7.35 ± 0.35 Aa	7.63 ± 0.36 Aa	7.51 ± 0.83 Aa	7.39 ± 0.83 Aa
[μmol·(min·g)$^{-1}$]	10–20	6.70 ± 0.03 Bb	7.14 ± 0.19 Ab	7.29 ± 0.32 Ab	8.15 ± 0.03 Aa	7.41 ± 0.50 Ab

Plot 1, *Z. planispinum* + *P. salicina*; plot 2, *Z. planispinum* + *S. tonkinensis*; plot 3, *Z. planispinum* + *A. hypogaea*; plot 4, *Z. planispinum* + *L. japonica*; plot 5, *Z. planispinum* monoculture plantation. Lower case letters indicate significant differences between different plantation types of the same depth at $p < 0.05$; upper case letters indicate significant differences between different depths of the same plantation types at $p < 0.05$. One-way ANOVA was used to calculate the differences, $p = 0.05$, n = 15. Data are presented as mean ± standard deviation.

Redundancy analysis (RDA) was performed with Canoco 4.5 software to investigate the main factors affecting soil quality and its effect on stoichiometry in different planting combinations of *Z. planispinum* plantations [28]. Due to the different dimensions of the data, the data were first pre-processed using normalization and centralization for data normalization before sorting. Data are presented as mean ± standard deviation. Column charts were created using Origin 8.6 (version 8.6, OriginLab Corporation, Northampton, MA, USA).

3. Results

3.1. Soil Properties of Z. planispinum Plantations with Different Planting Combinations

3.1.1. Soil Temperature, Water Content, and pH Value

Soil temperature (ST) was significantly lower in both soil layers in plot 1, but there was no significant difference between the rest of the plots. SWC values in both soil layers showed that plot 2 > plot 1 > plot 4 > plot 3 > plot 5, and the values were significantly higher in plot 2 than in plots 3 and 5 and increased with the deepening of the soil layer, indicating that the allocation of *P. salicina* could improve SWC. The pH values in the 0–10 cm soil layer were significantly higher in plots 3 and 5 than in plots 1 and 2 and significantly lower in plot 1 in the 10–20 cm soil layer, indicating that the combination with *P. salicina* had a certain effect on pH improvement (Figure 1).

3.1.2. Soil Available Nutrient Elements

Analysis of available N and available P contents in the 0–10 cm soil layer showed that both were higher in plots 1 and 4 than the other plots, and plot 5 was the lowest. The available K contents were plot 1 > plot 4 > plot 2 > plot 3 > plot 5. The available Ca contents were the highest in plot 4 and the lowest in plot 1, with significant differences between them. The available Mg contents were significantly higher in plots 4 and 5. The change law of the 10–20 cm soil layer was similar. In general, it seemed that the effect of the planting pattern on available nutrients was greater than that of total nutrients, especially on available Ca and available Mg. The combination with *P. salicina* and *L. japonica* was beneficial to the accumulation of available N, available P, and available K (Figure 2).

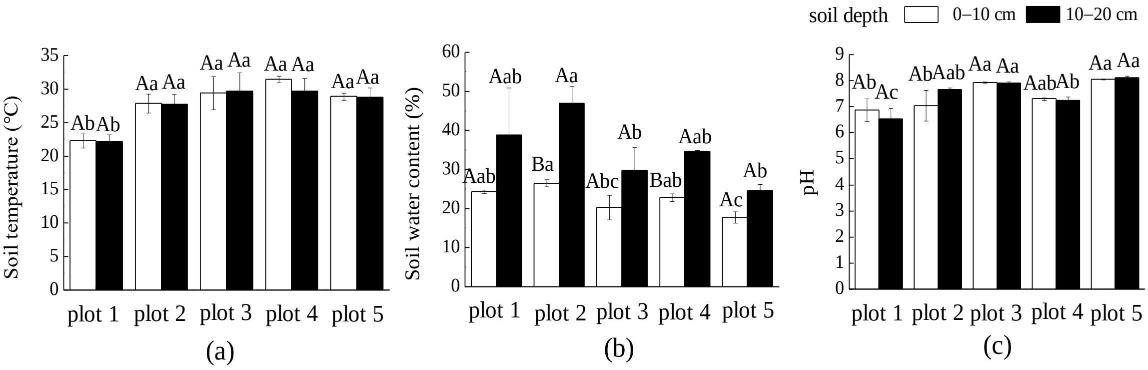

Figure 1. Soil temperature (**a**), water content (**b**) and pH value (**c**) of *Z. planispinum* plantations with different planting combinations. Plot 1, *Z. planispinum* + *P. salicina*; plot 2, *Z. planispinum* + *S. tonkinensis*; plot 3, *Z. planispinum* + *A. hypogaea*; plot 4, *Z. planispinum* + *L. japonica*; plot 5, *Z. planispinum* monoculture plantation. The vertical line on each bar is the error line, that is, the error range of the statistical results. The upper part is a positive error, and the lower part is a negative error. Lower case letters indicate significant differences between different plantation types of the same depth at $p < 0.05$; upper case letters indicate significant differences between different depths of the same plantation types at $p < 0.05$. One-way ANOVA was used to calculate the differences, $p = 0.05$, n = 15.

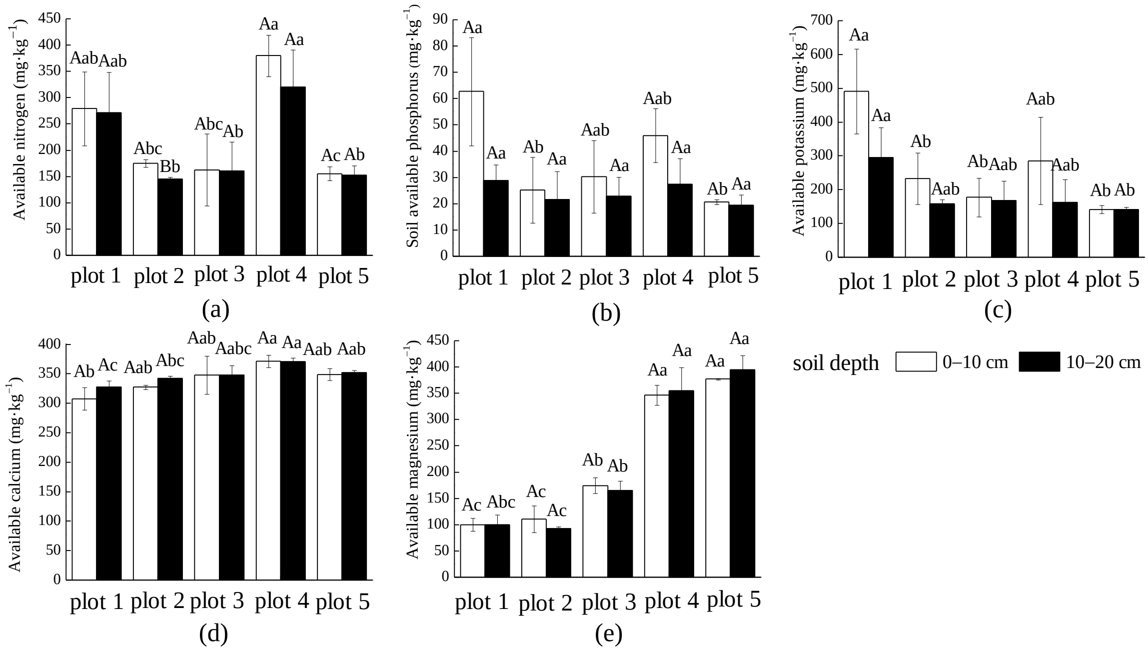

Figure 2. Soil available nitrogen (**a**), available phosphorus (**b**), available potassium (**c**), available calcium (**d**), available magnesium (**e**) of *Z. planispinum* plantations with different planting combinations. Plot 1, *Z. planispinum* + *P. salicina*; plot 2, *Z. planispinum* + *S. tonkinensis*; plot 3, *Z. planispinum* + *A. hypogaea*; plot 4, *Z. planispinum* + *L. japonica*; plot 5, *Z. planispinum* monoculture plantation. The vertical line on each bar is the error line, that is, the error range of the statistical results. The upper part is a positive error, and the lower part is a negative error. Lower case letters indicate significant differences between different plantation types of the same depth at $p < 0.05$; upper case letters indicate significant differences between different depths of the same plantation types at $p < 0.05$. One-way ANOVA was used to calculate the differences, $p = 0.05$, n = 15.

3.2. Comprehensive Evaluation of Soil Quality of Z. planispinum Plantations with Different Planting Combinations

Principal component analysis was conducted based on 24 soil quality indicators. According to the principle of eigenvalue > 1 and cumulative variance contribution rate > 85%, six principal components were extracted, with a cumulative contribution rate of 86.19%, indicating that they could explain the original variables. Therefore, further analysis was carried out for each principal component group loading factor (Table 4). Among them, the first principal component was significantly positively correlated with SOC, total N, total P, and available N, representing the soil mass elements C, N, and P. The second principal component had a large load on total Ca, total Mg, and available Mg, which are characteristic elements of karst areas. The third principal component had a large load on β-1,4-glucosidase (BG), β-1,4-N-acetylglucosaminidase (NAG), and acid phosphatase (AP), mainly due to soil extracellular enzyme activity. The main dominant index of the fourth principal component was microbial biomass (MB) P, which represented soil microbial biomass. The fifth principal component had a large load with bacteria, actinomycete concentration, and MBN, which represented soil microorganisms. The sixth principal component was mainly controlled by SWC and indicated the soil's physical properties.

Table 4. Load matrix of principal component analysis of soil quality of *Z. planispinum* plantations with different planting combinations.

Soil Parameters	Load Matrix of Principal Components					
	PC1	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**
pH	−0.579	0.673	0.081	0.194	−0.036	−0.016
Soil water content	−0.178	−0.423	−0.258	0.073	0.031	**0.768**
Soil temperature	−0.020	0.526	0.303	0.648	0.145	0.060
Soil organic carbon	**0.916**	−0.003	−0.097	0.279	0.155	0.042
Total nitrogen	**0.924**	0.067	0.039	0.267	0.120	0.043
Total phosphorus	**0.828**	0.352	0.056	−0.035	0.155	−0.279
Total potassium	0.075	0.564	0.359	0.415	−0.041	−0.341
Total calcium	−0.248	**0.865**	0.015	−0.112	−0.108	−0.013
Total magnesium	−0.108	**0.874**	0.096	0.074	−0.073	−0.303
Available nitrogen	**0.939**	−0.086	0.054	0.164	0.072	0.058
Soil available phosphorus	0.745	−0.246	0.062	−0.241	−0.194	−0.146
Available potassium	0.616	−0.361	0.042	−0.413	−0.482	−0.138
Available calcium	0.189	0.622	0.031	0.602	0.325	0.206
Available magnesium	0.169	**0.850**	0.224	0.222	0.014	−0.005
Fungi concentration	0.636	−0.235	0.177	−0.184	0.189	0.455
Bacterial concentration	0.314	−0.410	−0.035	0.035	**0.793**	0.120
Actinomycetes concentration	0.527	−0.207	0.071	−0.087	**0.746**	0.216
Microbial biomass carbon	0.077	0.364	0.505	−0.225	−0.044	0.525
Microbial biomass nitrogen	−0.169	0.308	0.236	0.016	**0.729**	−0.253
Microbial biomass phosphorus	0.140	−0.068	0.154	**0.844**	−0.111	−0.119
β-1,4-glucosidase	0.038	0.093	**0.969**	0.145	0.059	−0.027
β-1,4-N-acetylglucosaminidase	0.037	0.092	**0.969**	0.144	0.061	−0.028
Leucine aminopeptidase	−0.028	0.561	0.562	−0.168	0.038	−0.140
Acid phosphatase	0.035	0.093	**0.969**	0.143	0.059	−0.029
Eigenvalue	6.918	5.883	2.629	2.404	1.587	1.266
Variance contribution rate (%)	23.104	20.899	16.176	9.864	9.430	6.721
Cumulative variance contribution rate (%)	23.104	44.002	60.179	70.043	79.473	86.194

Bold font is the relatively large influence factor of each main component load factor.

According to Table 5, the SQIs of different plantations were obtained by weighting the variance contribution of each principal component factor and the factor scores as plot 4 > plot 5 > plot 3 > plot 2 > plot 1. The positive SQI values of plots 4 and 5 indicated that the soil fertility of these two plantations was higher than the average, and the *Z.*

planispinum + *L. japonica* plantation had the best soil quality, which was higher than the other plantations.

Table 5. Soil quality evaluation of *Z. planispinum* plantations with different planting combinations.

Plantation Type	Factor Score						Soil Quality Parameters	Rank
	F_1	F_2	F_3	F_4	F_5	F_6		
Plot 1	1.589	**−3.042**	−2.419	−2.678	−0.625	0.652	−0.939	5
Plot 2	−1.198	**−1.746**	−1.471	−0.703	0.001	1.542	−0.845	4
Plot 3	**−1.235**	0.630	0.430	0.801	−0.260	−1.023	−0.098	3
Plot 4	2.587	1.046	2.578	2.237	2.095	**0.386**	1.678	1
Plot 5	**−1.742**	3.113	0.882	0.343	−1.210	−1.558	0.206	2

Bold font is the factor with the lowest score.

3.3. Soil Stoichiometry of Z. planispinum Plantations with Different Planting Combinations

The variation of C:N in the same soil layer was not significant, and the trends of C:P and N:P were similar, with the highest values in plot 2 and the lowest values in plot 5. C:K, N:K, and P:K were generally the highest in plot 1 and the lowest in plot 3. The differences of soil microbial stoichiometry ratios were only reflected in the MBC:MBP in the 0–10 cm soil layer, which was significantly higher in plot 1 than in plots 2–4. The three extracellular enzyme stoichiometry ratios did not differ significantly among different sites in the same soil layer or among different soil layers in the same site (Table 6).

3.4. Effect of Soil Quality on Stoichiometry

After taking the minimum dataset to filter the factor ranking, more than 20% of information was lost. It also caused the contribution of individual factors to be reduced again due to secondary dimensionality reduction. Therefore, we tried to select all indicators for RDA. The 24 soil quality factors and SQI, totaling 25 indicators involved in the PCA, were subjected to RDA as environmental variables. The final amount of variability explained by environmental factors on 14 stoichiometric ratios was obtained. As shown in Figure 3, the explanation rate of axis1 and axis2 were 39.50% and 17.20%, respectively, with a cumulative explanation rate of 56.7%, indicating that axis1 and axis2 could explain more than half of the information. The red and blue arrows in the figure represent soil quality indicators (explanatory variables) and soil stoichiometry (response variables), respectively. A longer length of arrows indicates a greater effect of the explanatory variables. A longer projection of a dashed arrow line on the solid arrow line indicates a greater effect on the soil stoichiometric ratio.

The content of soil available nutrients and microbial concentrations had positive effects on element stoichiometry, but the effect of total nutrients was negative, suggesting that the balance relationships of elements were more governed by their available forms and quantities. There was a significant enhancement effect of SWC on C:N, C:P, N:P, and BG:(NAG + LAP), indicating that SWC weighed more on a large number of limiting elements such as C and N. The contribution of Ca and Mg elements to soil stoichiometry was relatively high in karst areas (Table 7), and the response of Ca:Mg to the explanatory variables was mostly negative compared with other stoichiometric ratios. SQI had little effect on soil stoichiometry (Table 7) and mainly showed inhibition, which indicated that attention should be paid to the action mechanism of different soil elements, especially nutrient elements. Soil microbial biomass stoichiometry ratios were relatively little influenced by soil habitat and tended to be internally stable mechanisms (Figure 3).

Table 6. Soil stoichiometric characteristics of *Z. planispinum* plantations with different planting combinations.

Soil Parameters	Soil Depth (cm)	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5
C:N	0–10	10.15 ± 1.49 Aa	11.70 ± 0.89 Aa	10.51 ± 1.05 Aa	11.69 ± 2.68 Aa	9.54 ± 0.29 Aa
	10–20	11.15 ± 0.09 Aa	10.50 ± 0.11 Aa	9.69 ± 2.59 Aa	10.12 ± 0.91 Aa	9.65 ± 0.29 Aa
C:P	0–10	25.08 ± 8.92 Aab	33.45 ± 4.88 Aab	25.70 ± 0.57 Aab	34.10 ± 5.62 Aa	20.50 ± 1.24 Ab
	10–20	30.97 ± 1.72 Aab	40.85 ± 7.13 Aa	26.08 ± 3.45 Ab	31.78 ± 4.15 Aab	21.63 ± 3.67 Ab
N:P	0–10	2.43 ± 0.52 Aa	2.88 ± 0.64 Aa	2.46 ± 0.30 Aa	2.94 ± 0.19 Aa	2.15 ± 0.19 Aa
	10–20	2.78 ± 0.18 Ab	3.89 ± 0.64 Aa	2.74 ± 0.38 Ab	3.13 ± 0.13 Aab	2.24 ± 0.31 Ab
C:K	0–10	5.08 ± 1.63 Aa	5.29 ± 1.91 Aa	2.60 ± 1.26 Aa	5.15 ± 1.63 Aa	2.30 ± 0.22 Aa
	10–20	5.86 ± 0.19 Aa	4.73 ± 0.36 Aab	2.11 ± 0.92 Ac	3.50 ± 1.01 Abc	2.60 ± 0.14 Ac
N:K	0–10	0.49 ± 0.09 Aa	0.46 ± 0.20 Aa	0.24 ± 0.10 Aa	0.44 ± 0.04 Aa	0.24 ± 0.03 Aa
	10–20	0.53 ± 0.01 Aa	0.45 ± 0.04 Aa	0.21 ± 0.04 Ac	0.34 ± 0.07 Ab	0.27 ± 0.01 Abc
P:K	0–10	0.20 ± 0.01 Aa	0.16 ± 0.03 Aab	0.10 ± 0.05 Ab	0.15 ± 0.02 Aab	0.11 ± 0.00 Ab
	10–20	0.19 ± 0.02 Aa	0.12 ± 0.03 Ab	0.08 ± 0.02 Ab	0.11 ± 0.02 Ab	0.12 ± 0.01 Ab
C:Ca	0–10	50.38 ± 15.96 Aa	25.39 ± 3.95 Aabc	16.41 ± 0.58 Abc	37.04 ± 14.75 Aab	4.59 ± 0.10 Ac
	10–20	37.62 ± 14.05 Aa	16.81 ± 5.60 Ab	14.28 ± 1.31 Ab	20.12 ± 0.57 Aab	4.26 ± 1.07 Ab
Ca:Mg	0–10	0.16 ± 0.02 Ac	0.24 ± 0.03 Ab	0.23 ± 0.04 Abc	0.20 ± 0.00 Abc	0.38 ± 0.03 Aa
	10–20	0.22 ± 0.08 Ab	0.39 ± 0.10 Aab	0.20 ± 0.03 Ab	0.25 ± 0.10 Ab	0.52 ± 0.16 Aa
MBC:MBN	0–10	21.61 ± 6.62 Aa	16.95 ± 0.88 Aa	15.96 ± 1.67 Aa	17.87 ± 0.89 Aa	19.88 ± 3.07 Aa
	10–20	18.34 ± 0.14 Aa	21.17 ± 2.61 Aa	19.63 ± 3.46 Aa	19.94 ± 0.75 Aa	17.64 ± 0.64 Aa
MBC:MBP	0–10	2.23 ± 0.27 Aa	1.69 ± 0.12 Abc	1.64 ± 0.01 Ac	1.53 ± 0.21 Ac	2.09 ± 0.11 Aab
	10–20	1.66 ± 0.35 Aa	1.86 ± 0.04 Aa	1.77 ± 0.14 Aa	1.92 ± 0.37 Aa	1.74 ± 0.33 Aa
MBN:MBP	0–10	0.11 ± 0.04 Aa	0.10 ± 0.01 Aa	0.11 ± 0.01 Aa	0.09 ± 0.01 Aa	0.11 ± 0.02 Aa
	10–20	0.09 ± 0.01 Aa	0.09 ± 0.01 Aa	0.09 ± 0.01 Aa	0.10 ± 0.02 Aa	0.10 ± 0.01 Aa
BG:(NAG + LAP)	0–10	0.10 ± 0.00 Aa	0.10 ± 0.00 Aa	0.10 ± 0.00 Aa	0.10 ± 0.00 Aa	0.09 ± 0.01 Aa
	10–20	0.10 ± 0.00 Aa	0.10 ± 0.00 Aa	0.10 ± 0.00 Aa	0.10 ± 0.00 Aa	0.10 ± 0.00 Aa
BG:AP	0–10	0.85 ± 0.00 Aa	0.85 ± 0.00 Aa	0.85 ± 0.00 Aa	0.85 ± 0.00 Aa	0.85 ± 0.00 Aa
	10–20	0.85 ± 0.00 Aa	0.85 ± 0.00 Aa	0.85 ± 0.00 Aa	0.85 ± 0.00 Aa	0.85 ± 0.00 Aa
(NAG + LAP):AP	0–10	8.73 ± 0.01 Aa	8.69 ± 0.10 Aa	8.75 ± 0.08 Aa	8.72 ± 0.20 Aa	9.42 ± 0.83 Aa
	10–20	8.52 ± 0.01 Bb	8.63 ± 0.06 Ab	8.67 ± 0.08 Ab	8.88 ± 0.01 Aa	8.7 ± 0.13 Aab

Plot 1, *Z. planispinum* + *P. salicina*; plot 2, *Z. planispinum* + *S. tonkinensis*; plot 3, *Z. planispinum* + *A. hypogaea*; plot 4, *Z. planispinum* + *L. japonica*; plot 5, *Z. planispinum* monoculture plantation. C:N, soil C:N ratio; C:P, soil C:P ratio; N:P, soil N:P ratio; C:K, soil C:K ratio; N:K, soil N:K ratio; P:K, soil P:K ratio; C:Ca, soil C:Ca ratio; Ca:Mg, soil Ca:Mg ratio; MBC:MBN, soil microbial biomass carbon to microbial biomass nitrogen ratio; MBC:MBP, soil microbial biomass carbon to microbial biomass phosphorus ratio; MBN:MBP, soil microbial biomass nitrogen to microbial biomass phosphorus ratio; BG:(NAG + LAP), ratio of β-1,4-glucosidase to the sum of β-1,4-n-acetylglucosaminidase and leu-cine aminopeptidase; BG:AP, β-1,4-glucosidase to acid phosphatase ratio; (NAG + LAP):AP, ratio of the sum of β-1,4-n-acetylglucosaminidase and leucine aminopeptidase to acid phosphatase. Lower case letters indicate significant differences between different plantation types of the same depth at $p < 0.05$; upper case letters indicate significant differences between different depths of the same plantation types at $p < 0.05$. One-way ANOVA was used to calculate the differences, $p = 0.05$, n = 15. Data are presented as mean ± standard deviation.

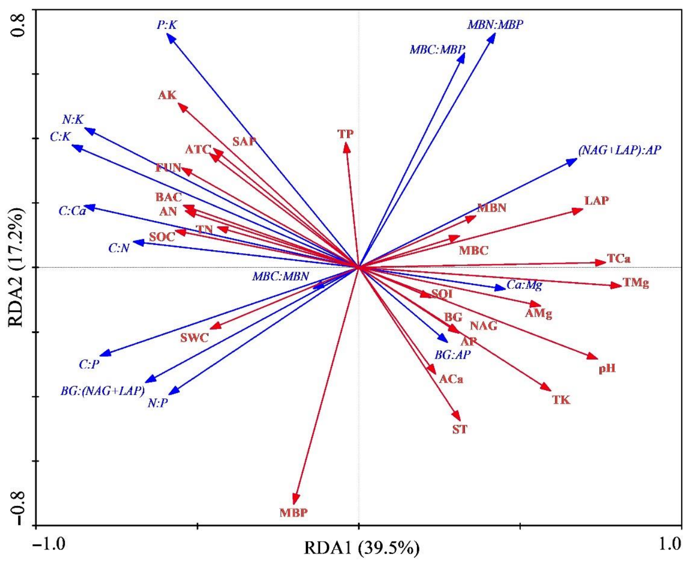

Figure 3. Two-dimensional sequence of the RDA analysis of soil quality and stoichiometry. ST, soil temperature; SWC, soil water content; SOC, soil organic carbon; TN, total nitrogen; TP, total

phosphorus; TK, total potassium; TCa, total calcium; TMg, total magnesium; AN, available nitrogen; SAP, soil available phosphorus; AK, available potassium; ACa, available calcium; AMg, available magnesium; FUN, fungi concentration; BAC, bacterial concentration; ACT, actinomycetes concentration; MBC, microbial biomass carbon; MBN, microbial biomass nitrogen; MBP, microbial biomass phosphorus; BG, β-1,4-glucosidase; NAG, β-1,4-N-acetylglucosaminidase; LAP, leucine aminopeptidase; AP, acid phosphatase; SQI, soil quality index.

Table 7. Importance ranking and significance test of soil quality index.

Soil Parameters	Importance Ranking	Factor Interpretation (%)	*p*	*F*
Total magnesium	1	27.3	0.002	10.5
Total calcium	2	26.0	0.002	9.8
pH	3	23.9	0.002	8.8
Leucine aminopeptidase	4	23.4	0.002	8.6
Available potassium	5	18.9	0.002	6.5
Total potassium	6	18.9	0.002	6.5
Soil organic carbon	7	15.2	0.002	5.0
Fungi concentration	8	15.1	0.002	5.0
Bacterial concentration	9	14.7	0.002	4.8
Available magnesium	10	14.1	0.002	4.6
Available nitrogen	11	14.1	0.006	4.6
Microbial biomass phosphorus	12	13.2	0.002	4.2
Soil water content	13	13.1	0.004	4.2
Soil available phosphorus	14	13.0	0.008	4.2
Actinomycetes concentration	15	12.6	0.006	4.0
Microbial biomass nitrogen	16	11.8	0.006	3.7
Acid phosphatase	17	10.5	0.010	3.3
β-1,4-glucosidase	18	10.5	0.012	3.3
β-1,4-N-acetylglucosaminidase	19	10.5	0.012	3.3
Total nitrogen	20	10.1	0.006	3.2
Soil temperature	21	10.1	0.010	3.2
Microbial biomass carbon	22	9.2	0.030	2.8
Total phosphorus	23	6.2	0.086	1.9
Soil quality index	24	6.2	0.088	1.9
Available calcium	25	6.0	0.114	1.8

4. Discussion

4.1. Comparison of Soil Quality of Z. planispinum Plantations with Different Planting Combinations

The soil SOC, total N, total P, available N, total Ca, total Mg, and available Mg were evaluated to represent the comprehensive level of soil fertility through principal component analysis (Table 4). At the same time, soil extracellular enzyme activity, microbial concentration and biomass also had a large effect, indicating that soil microorganisms can drive nutrient transformation and cycling, indirectly reflecting the level of comprehensive soil fertility [29].

The soil quality of *Z. planispinum* + *L. japonica* was the highest among the five plantations (Table 5). The reasons are as follows: 1, *L. japonica* produces a large amount of soft and easily decomposed litter [30], which is conducive to nutrient return and improves the content of soil C, N, P, K and other nutrients (Table 2, Figure 2); 2, *L. japonica* covers the soil and its shallow root system creates more suitable hydrothermal conditions for microbial mineralization of nutrients and increases the dynamic circulation of available nutrients in the soil [31]; and 3, the pH value of this plantation is close to neutral (Figure 1c), which facilitates the activation of effective soil nutrients [32]. The comprehensive results showed that *Z. planispinum* + *L. japonica* formed a vertical distribution pattern and a semi-closed soil environment, improved the spatial utilization efficiency and the surface microenvironment, and would be the optimal allocation pattern in a dry and hot karst valley.

Z. planispinum + *L. japonica* had the lowest factor score for factor 6 (Table 5), which was known to have low SWC (28.69%) from Figure 1b. The reason for this is that *L. japonica* has a high canopy density, and the canopy requires a large amount of water, which greatly reduces the water available in the soil. It is also because *L. japonica* has a higher demand for soil water during growth in order to maintain a high biomass. Therefore, in order to improve the soil quality of the plantation, the SWC needs to be increased to a suitable level. However, in a long-term arid environment, plants in karst areas form a physiological structure suitable for the habitat [33], so the appropriate soil water threshold needs to be further studied. *Z. planispinum* + *A. hypogaea* and monoculture *Z. planispinum* plantations had the lowest factor scores for factor 1 (Table 5), indicating that their soil quality was closely related to soil C, N, and P nutrient deficits. Meanwhile, *Z. planispinum* + *P. salicina* and *Z. planispinum* + *S. tonkinensis* plantations had the lowest factor scores for factor 2 (Table 5), indicating that both were influenced by the content of Ca and Mg elements. Ca and Mg are essential nutrient elements for plant growth and development and also participate in photosynthesis, senescence, and other physiological metabolic processes [16,34]. Since the contents of total Ca, total Mg and available Mg in the soil of the two plantations were lower than those of other plantations (Table 2, Figure 2e), additional Ca and Mg inputs were needed. According to Table 5, the SQI of monoculture *Z. planispinum* plantation was higher than that of *Z. planispinum* + *P. salicina*, *Z. planispinum* + *S. tonkinensis* or *Z. planispinum* + *A. hypogaea*, which was inconsistent with the conclusion that mixed forest can effectively increase soil fertility and improve the soil nutrient distribution pattern [35,36]. The reasons are as follows. First, the low nutrient return of the configured trees, coupled with their relatively concentrated root distribution, makes them compete with the *Z. planispinum* for nutrients, eventually leading to low soil nutrient content. In addition, among the three plantations, *P. salicina* and *A. hypogaea* both extracted a large amount of nutrients due to harvesting for consumption (for *L. japonica*, only a small number of flowers was removed), while *S. tonkinensis* formed a low perennial shrub with limited nitrogen fixation. Finally, soil fertility is also related to the production of specific root secretions by the configured trees, which affected the mutually beneficial relationship between plants and microorganisms [37,38]. It is clear that the selection of configured trees is crucial for improving soil quality. From the perspective of biodiversity maintenance and ecosystem function enhancement, organic carbon and organic nitrogen components can also be added in the future to assist in the screening of species.

4.2. The Driving Force of Soil Quality on Stoichiometry of Z. planispinum Plantations with Different Planting Combinations

Total nutrients characterize the potential of soil to supply nutrients to plants and are direct factors for calculating stoichiometric ratio. Available nutrients are the proportion that can be directly absorbed and utilized by microorganisms. As important nutrients for microbial growth, available nutrients affect the leaching and extraction of nutrients by microorganisms, indicate the chemical and biological processes of soil microorganisms, and regulate the proportion of elements in the soil [39]. As shown in Figure 3, available K had a synergistic effect on stoichiometry, while total K had the opposite effect, indicating that the effects of nutrient forms on ecological processes were different. The reason for this phenomenon may be that the deficiency of available nutrients stimulates the mineralization process of microorganisms so as to quickly provide nutrients required for the growth of plants and microorganisms [40]. Total nutrient deficiency accelerates the humification process to form a pattern of "intensive utilization" of nutrients [41], but the specific mechanism needs further research.

SWC affects nutrient dissolution, transport, and microbial activity, which in turn limits soil quality and vegetation growth. The SWC in this study was proportional to C:N, which was a key index affecting stoichiometry (Figure 3). This finding indicated that increased SWC led to slower soil mineralization rates and increased SOC content. This is consistent with the conclusion of Muhammad et al. [41] that SWC plays a catalytic role in SOC content, indicating that in dry environments where soil water is a limiting factor, high SWC can regulate the soil microenvironment and increase SOC accumulation through microbial activity. The SWC in this study was also proportional to both C:P and N:P (Figure 3), indicating that the increase of SWC promoted P fixation by soil microorganisms, resulting in the decrease of total P content accompanied by the decrease of P availability. The contributions of total Ca and total Mg were relatively highest among the soil nutrients affecting stoichiometry (Table 7), because Ca and Mg contents are high in the karst limestone geological background. *Z. planispinum* has developed a specific Ca-dependent mechanism through long-term evolution in this environment, and thus Ca and Mg have become the key dominant factors for its growth. The pH value can affect chemical reactions such as oxidation–reduction, neutralization, dissolution and precipitation in the soil, as well as the activity of microorganisms, and change the balance of soil elements [42]. In this study, pH was inversely proportional to C:N, indicating that the lower the pH the slower the mineralization of organic matter within a certain range. This is due to the fact that a suitable pH promotes microbial activities and accelerates organic matter decomposition, which in turn increases SOC [43]. The microbial biomass stoichiometric ratios were less influenced by elements and were mainly influenced by MBP (Figure 3). According to the homeostasis hypothesis, this phenomenon indicates that when the nutrient balance in the external environment changes, microorganisms adjust the community structure and metabolic process to maintain their own stoichiometric stability [44]. In this study, SQI has little effect on stoichiometry (Table 7). This is because soil is a "black-box" system, and the material exchange and nutrient circulation between plants and soil is a complex open system [45]. This suggests that it is important to consider not only the impact of the integrated soil quality on stoichiometry but also the trade-offs and synergistic relationships among the soil elements. Therefore, soil managers should not only pay attention to comprehensiveness but also strengthen the control of different elements, which has reference significance for the next step of soil quality regulation.

5. Conclusions

The order of SQI was *Z. planispinum* + *L. japonica* (1.678) > *Z. planispinum monoculture* (0.206) > *Z. planispinum* + *A. hypogaea* (−0.098) > *Z. planispinum* + *S. tonkinensis* (−0.845) > *Z. planispinum* + *P. salicina* (−0.939), indicating that *Z. planispinum* + *L. japonica* was the preferred planting combination. Redundancy analysis showed that SWC, pH, and other factors have a greater impact on stoichiometry, while SQI has a smaller impact. This indicates that there are strong interactions among the soil's physical, chemical and biological factors, which affects the geochemical processes of elements. Attention should be paid to the regulatory effect of different soil factors on their stoichiometry.

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