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Effects of Different Tillage and Residue Retention Measures on Silage Maize Yield and Quality and Soil Phosphorus in Karst Areas

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Abstract: Soil phosphorus (P) limitation in karst areas has severely constrained soil quality and land productivity. To enhance silage maize yield and quality and alleviate and/or balance the low phosphorus availability in the karst areas of China, the experiment investigated the effects of different tillage and residue retention practices on silage maize yield and quality and soil phosphorus in this region. The treatment set included: conventional tillage (CT), conventional tillage and root stubble retention (CTH), conventional tillage and mulch (CTM), conventional tillage and crushing and incorporation of hairy vetch by tillage (CTR), no tillage (NT), no tillage and root stubble retention (NTH), no tillage and mulch (NTM), and no tillage and living mulch (NTLM). The results showed that CTM, NTM, CTR, and NTLM significantly increased the height and LAI of silage maize compared with the CT, NT, and NTH treatments. CTM, CTR, and NTM significantly enhanced maize yield. Compared with conventional tillage, not tilling had a more pronounced improvement in silage quality, whereas residue retention hardly affected corn quality. In addition, although not tilling does not significantly increase acid phosphatase activity, it appeared to be advantageous in increasing soil microbial phosphorus and available phosphorus content when combined with cover crop measures. Ultimately, we concluded that NTM and NTLM are beneficial for silage maize yield and quality and soil phosphorus content in karst areas and verified the advantages of combining no tillage and residue retention practices for silage maize production and soil phosphorus improvement in the karst areas of China.

Keywords: conservation tillage; residue retention; maize; yield; soil phosphorus

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1. Introduction

Maize (*Zea mays*), as an important food and feed source worldwide, greatly affects global food security and energy needs [1]. Phosphorus (P), as an essential nutrient for plants, is crucial for crop growth and development, including photosynthesis, transpiration, and root growth [2,3]. With the degradation of agroecosystems, P has become a limited and non-renewable resource because of the weathering loss of primary mineral phosphorus and the significant loss of organic complexes during secondary accumulation processes. Its limitation in terrestrial ecosystems has posed great challenges to maize production globally [4].

Due to the fragile ecological conditions in karst regions, agricultural production in these areas has always been the biggest constraining factor limiting regional economic and social development [5]. In particular, poor water-holding capacity, weak disturbance resistance, and severe soil erosion are the main factors limiting agronomic productivity [6]. Moreover, P availability is always one of the limiting factors impacting soil productivity in karst regions [7]. Furthermore, the development of rocky desertification, the reduction of healthy arable land, and low phosphorus utilization efficiency have greatly challenged maize yield and quality in this region.

Conservation agriculture measures, including reduced soil disturbance and cover crops, have been widely recognized for their contribution to maintaining soil quality in agricultural production [8,9]. Specifically, no-tillage (NT) measures can improve soil structure, maintain the stability of macroaggregates, and increase soil organic matter content [10]. This improvement is also accompanied by the enhancement of soil biological functions, including phosphatase activity, microbial biomass, and the abundance of phosphate-solubilizing microbial communities [11]. Although some studies suggest that no-tillage farming benefits soil phosphorus availability [12,13], the impact of no-tillage farming on soluble phosphorus loss in soil remains controversial [14,15]. Additionally, the negative effects of no-tillage farming on maize yield should not be overlooked. Pittelkow et al. [16] argue that no-tillage farming must be combined with other conservational agricultural measures to exert a positive effect on yield. Chețan et al. [8] believe that combining no tillage with cover crop measures can increase silage maize yield, crude protein, and crude fat content. Undoubtedly, cover crops contribute to soil carbon sequestration and soil nitrogen storage [17]. Although cover crop residue decomposition can serve as a source of soil phosphorus accumulation to some extent [15], the impact on soil phosphorus availability and whether the accumulated phosphorus can offset production consumption to maintain soil fertility and enhance crop yield and/or quality remains unknown.

Here, this study investigates the changes in maize yield, quality, and soil phosphorus under different tillage and cover crop practices in karst regions. The objectives were to explore (i) how tillage practices influence maize yield and quality and soil phosphorus, (ii) the combined effects of tillage practices and cover crop practices on maize yield and quality and soil phosphorus, and (iii) what the inter-relationship is between maize yield and quality, soil phosphorus, and phosphatase activity. The answers to these questions will contribute to a deeper understanding of soil phosphorus status in karst regions and provide preliminary knowledge and scientific evidence as a basis for further clarification of which conservation agriculture practices (tillage and residue retention) can maximize silage maize productivity and alleviate soil phosphorus limitation in karst regions.

2. Methods

2.1. Experimental Site

The experimental site was located at the experimental base of Guizhou Oilseed Rape Research Institute, Tangtou Town, Sinan County, Tongren City, Guizhou Province (27°44′ N, 108°11′ E), at an altitude of 386 m (Figure 1a). The average annual rainfall is about 1142 mm, and the average annual temperature is about 17.5 °C, which is a typical central subtropical monsoonal humid climate (Figure 1b). The soil type in the test area was orthic Acrisol (FAO taxonomy), and the basic physicochemical properties of the soil before the test are shown in Table 1. The previous crop was hairy vetch (*Vicia villosa*).

2.2. Experimental Design

The experiment was established in 2021 and repeated for a second year. Each plot was 8 m × 7.8 m in size, but sampling area was contained within the center 6 m × 5.4 m area to avoid edge effects. Silage maize, Qianqing 446, was sown on 8 April 2022. It used a randomized complete block design with a split-plot and factorial arrangement. The treatments included combinations of tillage and residue retention practices (Table 2). Three replicates were set up for each treatment, for a total of 24 plots. Each plot was planted in a sampling area in a wide (80 cm)–narrow (40 cm) row pattern. The plant spacing was 20 cm and the sowing density was 92,000 plants ha^{-1}. A compound fertilizer ($N:P_2O_5:K_2O$ = 15:15:15) at 150 kg ha^{-1} was applied before sowing and urea at 73.5 kg ha^{-1}

and 122.25 kg ha^{-1} was used at the jointing stage and big trumpet stage, respectively. Weeds found during the growing period were managed by hand-pulling, and other management methods were consistent with the local practices.

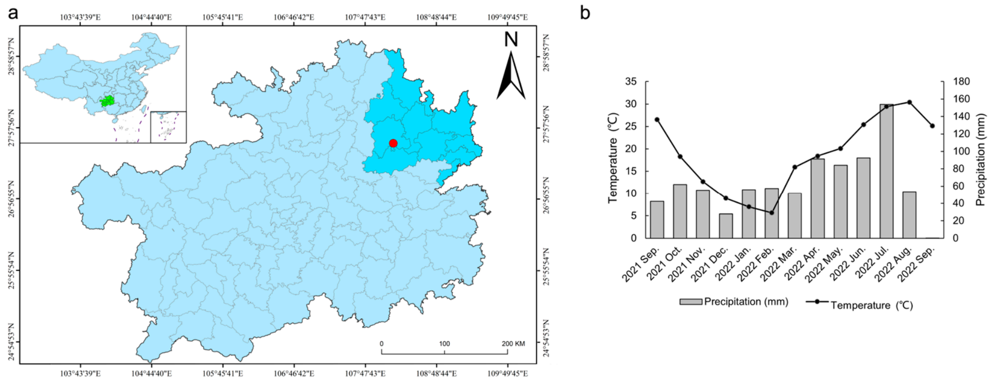

Figure 1. (**a**) Study location in southeastern China. (**b**) The precipitation and mean temperature of the maize growing season in the study area in 2021–2022.

Table 1. Basic soil properties of soil depth (0–100 cm) before the experiment.

Soil Layer (cm)	**pH**	**SOC (g kg^{-1})**	**TN (g kg^{-1})**	**NO_3 (mg kg^{-1})**	**NH_4 (mg kg^{-1})**	**TP (g kg^{-1})**	**AP (mg kg^{-1})**
0–5	5.29	20.71	1.74	52.00	2.82	0.74	35.64
5–10	5.39	20.52	1.52	36.75	1.23	0.66	30.92
10–20	5.37	18.39	1.49	23.60	0.50	0.67	35.17
20–30	5.73	16.10	1.17	12.01	0.30	0.61	25.08
30–45	5.93	14.73	1.07	9.73	0.26	0.53	18.65
45–60	5.91	13.76	0.94	9.31	0.25	0.62	18.28
60–80	5.80	15.24	1.13	7.49	0.91	0.48	19.70
80–100	5.68	16.03	1.21	11.78	1.09	0.48	19.41

Notes: soil organic carbon (SOC), total nitrogen (TN), available nitrogen (NO_3, NH_4), total phosphorus (TP), available phosphorus (AP).

Table 2. Description of tillage and residue retention practices.

Treatments	**Tillage**	**Residue Retention**
CT	Conventional tillage (tillage with machinery at a depth of 30 cm before sowing)	No hairy vetch
CTH	Conventional tillage (tillage with machinery at a depth of 30 cm before sowing)	Above-ground harvest of hairy vetch and root stubble retention
CTM	Conventional tillage (tillage with machinery at a depth of 30 cm before sowing)	Mulch after above-ground harvest of hairy vetch
CTR	Conventional tillage (tillage with machinery at a depth of 30 cm before sowing)	Crushing and incorporation of hairy vetch by tillage
NT	No tillage	No hairy vetch
NTH	No tillage	Above-ground harvest of hairy vetch and root stubble retention
NTM	No tillage	Mulch after above-ground harvest of hairy vetch
NTLM	No tillage	Living mulch (above-ground stubble of hairy vetch left for 5 cm to maintain growth until silage maize harvest)

2.3. Plant Sample and Analysis

After the seedling stage, 9 plants of uniform and representative silage corn were randomly selected and marked in each plot. Silage maize plant height (vertical height from the ground to the highest part of the maize in its natural state), leaf length (length from the tip of the leaf to the base of the leaf), and leaf width (length at the widest part of the leaf) were measured at the jointing stage, big trumpet stage, and milk stage, respectively.

After measuring the above indexes, nine plants were destructively sampled to measure biomass (except fixed plants) at the jointing and big trumpet stages and the entire sampling plot was harvested at milk stage to determine yield. Specifically, the sampled plants were dried at 105 °C for 30 min, then dried at 65 °C to a constant weight before dry matter was measured [18]. The dried samples were pulverized with a plant powder sampler and sealed through a 0.35 mm sieve for storage. The samples were used for the determination of crude fiber (CF), crude ash (Ash), and crude fat according to Pearsons et al. [19] and total nitrogen (TN), neutral detergent fiber (NDF), and acid detergent fiber (ADF) content via Kjeldahl nitrogen determination, the salicylic acid colorimetric method, the indotrione colorimetric method, and Van's cellulose content determination method [20,21].

The leaf area index (*LAI*) was calculated as follows:

$$S_1 = L \times W \times 0.75 \tag{1}$$

$$LAI = \frac{S_1 \times n}{A} \tag{2}$$

where S_1 is the leaf area of single maize plant (cm^2), L is leaf length (cm), W is leaf width, the leaf area coefficient is 0.75 (the leaf area coefficient of unexpanded leaves was 0.5), n is number of corn plants per unit area, and A is the unit land area (cm^2).

The crude protein (*CP*) was calculated as follows:

$$CP = TN \times 6.25 \tag{3}$$

where *TN* is the total nitrogen of maize plant (cm^2) and there is a conversion factor of 6.25.

2.4. Soil Sample and Analysis

After silage maize harvest, samples were taken at 0–5 cm and 5–10 cm depths using the five-point method. Samples from the same soil layer in the same plot were mixed uniformly to remove sand and gravel and plant residues and then dried naturally, ground, and passed through a 2 mm screen for soil property analysis and enzyme activity determination. Total phosphorus (TP) was measured using the H_2SO_4–$HClO_4$ elimination method. Available phosphorus (AP) was measured using the $NaHCO_3$ extraction/Mo-Sb colorimetric method [13]. Soil microbial phosphorus (MBP) was determined using the chloroform fumigation method, and the acid phosphatase (ACP):sodium ratio was determined using the benzene phosphate colorimetric method [22].

2.5. Data Analysis

We used univariate analysis of variance (ANOVA, $p < 0.05$) to test the effects of different treatments on maize yield and quality, soil phosphorus content, and enzyme activities. Duncan's multiple range test was used for mean separation. The R "corrplot" package was used to calculate the Pearson's correlation matrix between plant and soil indices, and the "ggcorrplot" package was used for data visualization.

3. Results

3.1. Maize Productivity and Quality

The effect of different tillage and residue retention practices on plant height was consistent across all periods (Table 3). Specifically, the CTHM, CTR, and NTM treatments were significantly greater than the CT, NT, and NTH treatments. NTLM treatment was significantly greater than the NT and CT treatments. CTH treatment was significantly greater than NT treatment. There were no significant effects for different tillage and residue retention practices on LAI at the jointing stage. At the big trumpet stage, CTM treatment was significantly greater than the CT, NT, and NTH treatments. CTR treatment was significantly greater than the CT and NT treatments. The NTM and NTLM treatments were significantly greater than NT treatment. At the milk stage, CTM treatment was significantly greater than all the other treatments except for CTR treatment. CTR treatment was significantly greater than the CTH, CTH, and NTH treatments. NTM treatment was significantly greater than the CT, NT, and NTH treatment. NTLM treatment was significantly greater than the CT and NT treatments. CTH treatment was significantly greater than NT treatment.

Table 3. Mean plant height and leaf area index (LAI) under different treatments and at different growth stages for conventional tillage (CT), conventional tillage and root stubble retention (CTH), conventional tillage and mulch (CTM), conventional tillage and crushing and incorporation of hairy vetch by tillage (CTR), no tillage (NT), no tillage and root stubble retention (NTH), no tillage and mulch (NTM), and no tillage and living mulch (NTLM).

Index	Treatment	Growth Stage		
		Jointing Stage	Big Trumpet Stage	Milk Stage
Height (cm)	CT	88.17 cd	169.07 cd	231.83 cd
	CTH	100.43 abc	192.20 abc	264.12 abc
	CTM	114.33 a	219.90 a	301.30 a
	CTR	112.12 a	215.40 a	295.23 a
	NT	81.03 d	155.97 d	213.01 d
	NTH	92.22 bcd	176.07 bcd	241.92 bcd
	NTM	108.07 a	207.57 a	284.90 a
	NTLM	105.87 ab	202.37 ab	277.32 ab
LAI	CT	1.12 a	2.40 cd	4.64 de
	CTH	1.28 a	2.73 abcd	5.29 bcd
	CTM	1.46 a	3.12 a	6.03 a
	CTR	1.43 a	3.05 ab	5.91 ab
	NT	1.03 a	2.21 d	4.26 e
	NTH	1.17 a	2.50 bcd	4.84 cde
	NTM	1.38 a	2.95 abc	5.70 b
	NTLM	1.34 a	2.87 abc	5.55 bc

Notes: Different letters indicate significant differences between different soil layers in the same treatment at the $p < 0.05$ level.

At the jointing stage, the biomass (Figure 2) and dry matter (Figure 3) in the CTM and CTR treatments were significantly greater than that in NT; the differences between the remaining treatments were not significant. At the big trumpet stage, the biomass in CTM treatment was significantly greater than that of the CTH, CTH, NR, and NTH treatments (Figure 2). Additionally, the biomass in NT treatment was significantly lower than in the CTH, CTR, NTM, and NTLM treatments. At the milk stage, the biomasses of the CTM and CTR treatments were significantly greater than that of the CT and NT treatments. The biomass in the NTLM and NTM treatments was significantly greater than in NT treatment.

For the CP percentage, the NT treatment and any of the overlay treatments under the NT practices were significantly greater than the CT treatment; the differences between the remaining treatments were not significant (Table 4). The CF percentage was significantly greater in NTM treatment than in the CT and NT treatments; the difference between the remaining treatments was not significant. The percentage of crude fat was significantly greater in the CTH, CTM, and CTR treatments than in CT treatment, whereas the remaining treatments did not differ significantly. No significant effects of tillage and residue retention practices on ADF, NDF, and Ash were found.

3.2. Soil Phosphorus Content and Phosphatase Activity

In the 0–5 cm soil layer, there was no significant difference in soil TP content among the treatments (Table 5), the AP content in CTM treatment was significantly greater than that in the NT and NTLM treatments, and there was no significant difference among the remaining treatments. The MBP content in CTM treatment was significantly greater than that in the other treatments except for NTM treatment. The MBP contents in the NTM and NTLM treatments were significantly greater than that in the CT and CTH treatments. The ACP activity was significantly greater in CTM treatment than in the other treatments, and the CTR and NTLM treatments were significantly greater than the NTM, NT, and CT treatments. The ACP activity was significantly lower in NT treatment than in other treatments, and CT treatment was significantly lower than other treatments.

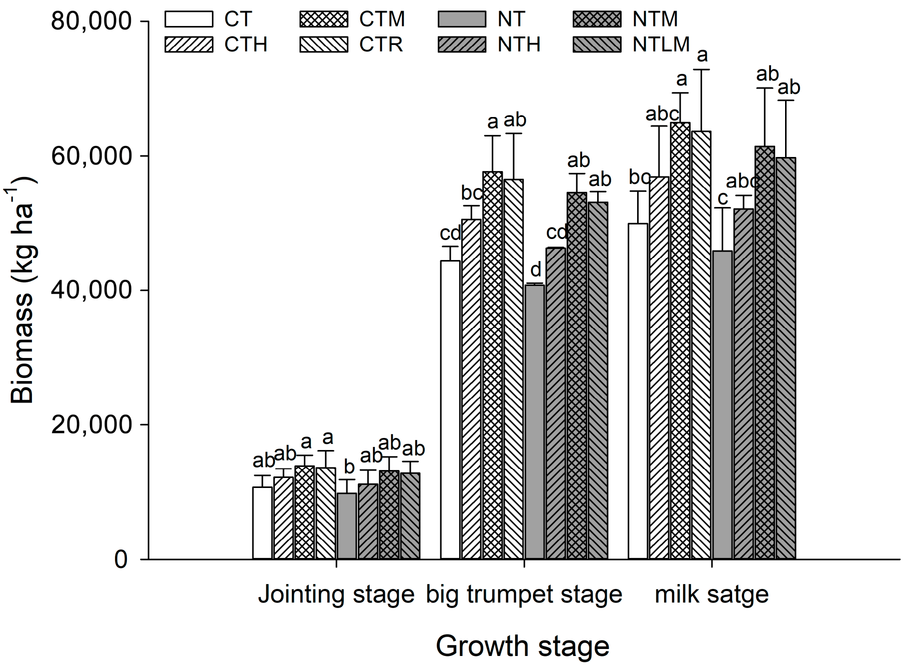

Figure 2. The biomass of maize at different growth stages in the study area. Notes: conventional tillage (CT), conventional tillage and root stubble retention (CTH), conventional tillage and mulch (CTM), conventional tillage and crushing and incorporation of hairy vetch by tillage (CTR), no tillage (NT), no tillage and root stubble retention (NTH), no tillage and mulch (NTM), and no tillage and living mulch (NTLM). Notes: Different letters indicate significant differences between different soil layers in the same treatment at the $p < 0.05$ level.

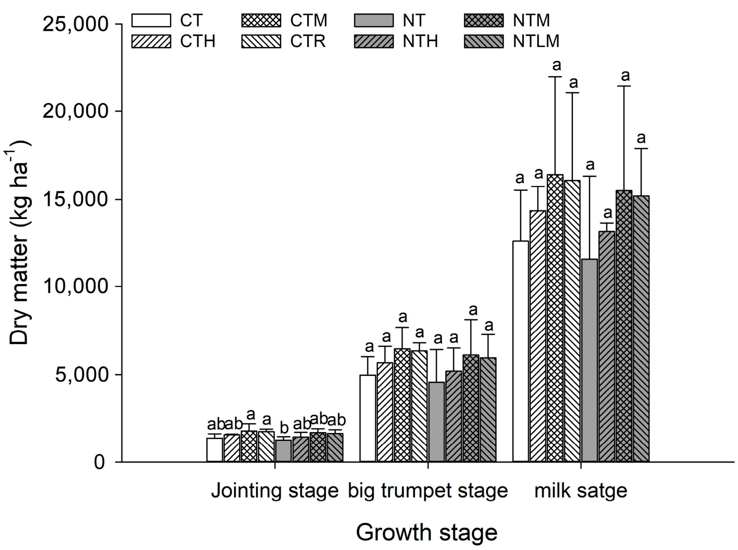

Figure 3. The dry matter of maize at different growth stages in the study area. Notes: conventional tillage (CT), conventional tillage and root stubble retention (CTH), conventional tillage and mulch (CTM), conventional tillage and crushing and incorporation of hairy vetch by tillage (CTR), no tillage (NT), no tillage and root stubble retention (NTH), no tillage and mulch (NTM), and no tillage and living mulch (NTLM). Notes: Different letters indicate significant differences between different soil layers in the same treatment at the $p < 0.05$ level.

Table 4. Mean crude protein (CP), crude fiber (CF), acid detergent fiber (ADF), neutral detergent fiber (NDF), crude ash (Ash), and crude fat under different treatments at the milk stage for conventional tillage (CT), conventional tillage and root stubble retention (CTH), conventional tillage and mulch (CTM), conventional tillage and crushing and incorporation of hairy vetch by tillage (CTR), no tillage (NT), no tillage and root stubble retention (NTH), no tillage and mulch (NTM), and no tillage and living mulch (NTLM).

Treatment	CP	CF	ADF	NDF	Ash	Crude Fat
	(%)	(%)	(%)	(%)	(%)	(%)
CT	7.38 b	23.91 b	30.27 a	50.43 a	6.76 a	1.66 b
CTH	8.13 ab	25.69 ab	32.17 a	54.12 a	6.38 a	2.85 a
CTM	8.09 ab	27.12 ab	30.69 a	49.63 a	7.17 a	2.96 a
CTR	8.18 ab	26.77 ab	30.65 a	52.34 a	7.20 a	3.08 a
NT	8.34 a	23.47 b	27.78 a	50.49 a	5.08 a	2.24 ab
NTH	8.53 a	26.10 ab	31.44 a	51.13 a	5.49 a	2.51 ab
NTM	8.91 a	29.71 a	32.76 a	53.61 a	5.61 a	2.98 ab
NTLM	8.69 a	28.57 ab	29.04 a	51.66 a	5.97 a	2.98 ab

Notes: Different letters indicate significant differences between different soil layers in the same treatment at the $p < 0.05$ level.

Table 5. Mean total phosphorus (TP), available phosphorus (AP), acid phosphatase (ACP), and soil microbial phosphorus (MBP) under different treatments at the growth stage for conventional tillage (CT), conventional tillage and root stubble retention (CTH), conventional tillage and mulch (CTM), conventional tillage and crushing and incorporation of hairy vetch by tillage (CTR), no tillage (NT), no tillage and root stubble retention (NTH), no tillage and mulch (NTM), and no tillage and living mulch (NTLM).

Soil Layer	Treatment	TP	AP	ACP	MBP
(cm)		(g kg^{-1})	(g kg^{-1})	(U g^{-1})	(mg kg^{-1})
0–5	CT	0.74 a	32.15 ab	73.63 d	22.03 c
	CTH	0.75 a	34.02 ab	105.79 bc	23.94 c
	CTM	0.65 a	41.12 a	156.99 a	45.18 a
	CTR	0.74 a	34.13 ab	121.53 b	28.86 bc
	NT	0.70 a	25.83 b	44.40 e	28.00 bc
	NTH	0.71 a	31.39 ab	117.79 bc	29.47 bc
	NTM	0.72 a	33.17 ab	100.32 c	40.02 ab
	NTLM	0.74 a	30.51 b	119.97 b	30.77 b
5–10	CT	0.67 c	24.91 c	67.11 e	18.26 c
	CTH	0.75 b	41.76 ab	94.34 d	18.98 c
	CTM	0.67 c	40.52 ab	150.77 a	25.26 b
	CTR	0.64 c	34.31 abc	129.32 b	19.23 c
	NT	0.72 abc	31.48 bc	40.64 f	21.76 bc
	NTH	0.71 bc	35.62 abc	97.67 d	27.27 abc
	NTM	0.65 c	38.99 ab	98.56 d	41.28 a
	NTLM	0.85 ab	46.08 a	113.57 c	25.34 b

Notes: Different letters indicate significant differences between different soil layers in the same treatment at the $p < 0.05$ level.

In the 5–10 cm soil layer, the TP content in NTLM treatment was significantly greater than in the four treatments of CT, CTM, CTR, and NTM (Table 5). CTH treatment was significantly greater than the CT, CTM, CTR, and NRM treatments. The AP content in NTLM treatment was significantly greater than that in the CT and NT treatments. The AP content in CT treatment was significantly lower than that in the CTH, CTM, and NTM treatments. The MBP content in NTM treatment was significantly greater than that in the other treatments except for NTH treatment. The CTM and NTLM treatments were significantly greater than the CTH, CTH, and CTR treatments, whereas the remaining treatments were not significantly different. CTM treatment had the highest ACP activity, followed by the CTR, NTLM, NTM, NTH, CTH, CT, and NT treatments. There were no significant differences between the CTH, NTH, and NTM treatments, and significant differences were found among the remaining treatments.

3.3. Correlation Analysis

From the results of correlation analysis, the relationship between TP and Ash was significantly negatively correlated ($p < 0.05$; Figure 4). There was a significant positive correlation between Ash and AP, LAI, and biomass ($p < 0.05$). AP had a highly significant positive correlation with LAI and biomass ($p < 0.01$) and a significant positive correlation with height and ACP ($p < 0.05$). Dry matter had a highly significant positive correlation with height ($p < 0.01$) and a significant positive correlation with biomass and CF ($p < 0.05$). LAI had a highly significant positive correlation with biomass, MBP, and ACP ($p < 0.01$) and a significant positive correlation with crude fat ($p < 0.05$). MBP had a highly significant positive correlation with biomass ($p < 0.01$) and a significant positive correlation with height, ACP, and crude fat ($p < 0.05$). Biomass had a highly significant positive correlation with height and ACP ($p < 0.01$) and a significant positive correlation with CF and crude fat ($p < 0.05$). Height had a highly significant positive correlation with ACP ($p < 0.01$) and a significant positive correlation with CF ($p < 0.05$). There was a significant positive correlation between ACP and CF and crude fat ($p < 0.05$). There was a significant positive correlation between crude fat and CP ($p < 0.05$). CF had a highly significant positive correlation with ADF ($p < 0.01$) and a significant positive correlation with CP and NDF ($p < 0.05$). There was a highly significant positive correlation between ADF and NDF ($p < 0.01$).

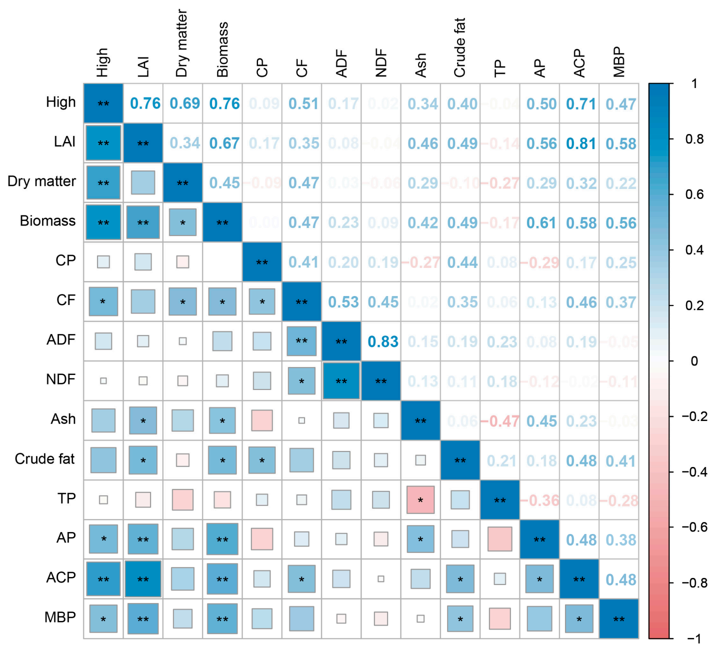

Figure 4. Correlation matrix between leaf area index (LAI), height, biomass, dry matter, crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), crude fiber (CF), crude ash (Ash), total phosphorus (TP), available phosphorus (AP), soil microbial phosphorus (MBP), and acid phosphatase (ACP). The confidence interval is 95%. * and ** indicate the significant effects of farming practices at $p < 0.05$ and $p < 0.01$, respectively, determined by Pearson's correlation.

4. Discussion

4.1. Impact of Different Tillage and Cover Measures on Soil Phosphorus and Phosphatase Enzymes

Different agricultural practices and cover crop management measures can affect the soil physicochemical properties, the soil phosphorus content, and the soil phosphatase activity, thus influencing the absorption and utilization of soil phosphorus by crops. The research results of Chen et al. [14] showed that compared with conventional tillage, no-tillage farming significantly increased the total phosphorus content in the 0–10 cm soil layer. At the same time, no-tillage farming can significantly enhance the available phosphorus content in the surface soil layer [13] and increase the microbial biomass, abundance of phosphate-solubilizing microorganisms [11], and phosphatase activity [22], which is inconsistent with our results. The results of this study indicated that although the average values for TP, AP, and MBP contents under no-tillage conditions were higher than those under conventional tillage (5–10 cm), no significant improvement was observed. On one hand, the effect of tillage practices on soil physicochemical properties may be confounded by different soil types [23]. On the other hand, this may be related to the duration of the experiment (the second year of establishing the conservation tillage system in this study), as experimental duration can have significant effects on soil nutrient content and nutrient availability [12,13]. The relationship between crops, soil, and microorganisms is complex, and no-tillage farming mainly improves the soil physical structure [10], increases soil organic matter content, reduces the loss of phosphorus due to adsorption, and provides conditions for the functioning of soil's biological functions, such as those suitable for microorganisms and enzymes [14]. Therefore, we believe that no-tillage farming may not significantly increase soil phosphorus content and nutrient availability in the short term [15].

Interestingly, this study found that conventional tillage significantly increased ACP activity in the 0–10 cm soil layer. It is generally believed that enzyme activity is positively correlated with microbial biomass; this was also observed in our correlation analysis [22]. However, we did not observe a significant increase in microbial biomass with conventional tillage, so we believe that this may be related to the loss of unstable soil organic carbon pools and/or soil organic matter [24]. It can also be argued that soil disturbance and aeration conditions from conventional tillage do not affect microbial biomass but rather microbial community composition [25], suggesting that some aerobic species may provide greater APC activity, such as mycorrhizal fungi [26]. The disruption of soil macroaggregates and the loss of organic matter due to tillage can cause microbial stress, leading to enzyme enrichment or increased metabolic activity [24]. Nevertheless, this study still focuses on conservation tillage systems, where no tillage combined with cover crop measures (especially residue retention and living mulch) significantly increased the contents of TP, AP, and MBP in the soil. The implications of this are multifaceted. Firstly, cover crops are important sources of nutrients and the decomposition of leguminous plants releases phosphorus [27]. This suggests that Vicia villosa roots attract particular microorganisms that are responsible for organic matter degradation and higher phosphorus availability [11,28]. Additionally, at low soil pH fungi may be important microbiota [22]. Secondly, no-tillage farming provides conditions for improving phosphorus availability by minimizing soil disturbance, maintaining stable physical structure, and reducing the loss of available phosphorus adsorption [29].

4.2. Impact of Different Tillage and Cover Measures on Maize Yield and Quality

The impact of tillage practices on crop yield is influenced by various factors such as the crop type and climatic conditions [16,30]. In this study, it was found that under no-cover-crop conditions, the biomass, plant height, and leaf area index (LAI) of the NT treatment were lower than those under CT, but the difference was not significant. This is consistent with the findings of Pittelkow et al. [16], who concluded that no tillage and conventional tillage have comparable yields. This may be attributed to the compaction of the soil caused by the absence of tillage, which to some extent affects the growth of crop roots [31]. Furthermore, it was observed that the yield of conventional tillage combined with a cover crop was comparable with that of no tillage combined with a cover crop. This is consistent with the results of Zhang et al. [10], indicating that although not tilling increases the proportion of soil macroaggregates and enhances the accumulation of surface soil nutrients, it does not significantly increase biomass under the same cover crop management. This suggests that tillage practices do not appear to be the determining factor for maize yield and that their impact on maize yield is variable [16]. Additionally, it was found that no tillage combined with cover crop retention and/or living mulch significantly increased yield compared with the fallow treatment under no-till conditions. Therefore, the combination of no tillage and cover crop measures may be an effective approach to maintain or even increase yield. On one hand, this could be due to the fact that the decomposition of the cover crop provides certain nutrient resources throughout the entire silage maize growth period, thus increasing maize yield [32]. On the other hand, under the conditions of living mulch, the roots of the cover crop can improve the soil structure, reduce compaction, and promote the growth of subsequent crops [33]. At the same time, microbial communities attracted by cover crop roots (living mulch) can improve soil nutrient availability and water accessibility and produce stimulating substances, thus supporting corn growth and increasing productivity [22]. Wang et al. [34] also found that not tilling had no significant effect on maize yield; however, the yield changed when combined with cover crop retention. Furthermore, it was observed that different utilization methods for cover crops have different effects on silage maize yield. This is consistent with the findings of Coombs et al. [32], which showed that using legume cover crops can improve maize nitrogen conditions and subsequently affect maize growth and yield. The increase in crop yield after incorporating cover crops through rolling and tilling may be due to the promotion of nitrogen and phosphorus nutrient accumulation in silage maize after tillage [17].

This study found that no-tillage conditions significantly increased the crude protein content of maize, whereas the addition of cover crop measures balanced the negative impact of conventional tillage on crude protein content. Clearly, not tilling has a positive effect on soil nutrients and enhances maize's utilization of nitrogen [8]; however, the contribution of legume cover crops on soil nitrogen cannot be ignored [19]. The present study also found that cover crops significantly increase the crude fat content of silage maize and that the combination of no tillage and cover crops also enhances it (although not significantly); moreover, there is a significant positive correlation between crude fat and MBP. This is consistent with the findings of Harish et al. [35], who concluded that no-tillage conditions, additional phosphorus input (cover crop decomposition), and high microbial biomass significantly increase the crude fat content of silage maize. Although the current results show that no-tillage conditions and cover crops do not play a significant role in improving maize yield and quality and soil phosphorus availability in all growth phases, the advantages of conservation tillage systems on soil health are still evident. Therefore, we can further determine the advantages of conservation tillage from the perspective of soil microbial communities. This could be performed by isolating rhizosphere microorganisms from Vicia villosa and maize and comparing them to identify microbiomes with higher key functions or importance resulting from conservation tillage and residue retention measures, which would also facilitate production to significantly increase maize productivity through the microbial fertilizer replacement of mineral fertilizers.

5. Conclusions

This study investigated the effects of different tillage and cover crop measures on silage maize yield and quality and soil phosphorus in karst areas. It provides a basis for identifying which conservation agriculture measures (tillage and residue retention) can maximize silage maize productivity and alleviate soil phosphorus limitations in karst areas. The results showed that the CTM, NTM, CTR, and NTLM treatments significantly increased the height and LAI of silage maize compared with CT, NT, and NTH treatments. The CTM, CTR, and NTM treatments significantly enhanced maize yield. Compared with conventional tillage, no tillage had a more pronounced improvement in silage quality, whereas residue retention hardly affected corn quality. In addition, although not tilling did not significantly increase ACP activity, it indicated positive effects by increasing MBP and AP content when combined with cover crop measures. Therefore, combining no tillage with cover crops should be promoted in silage maize production in the karst areas of China. Nevertheless, we also need to conduct longer-term experiments and further exploration of soil phosphorus cycling, such as soil phosphorus fractions, isotope experiments, cover crop decomposition experiments, etc., to validate the advantages of conservation tillage in silage maize cropping systems.

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