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Improving Soil Fertility and Wheat Yield by Tillage and Nitrogen Management in Winter Wheat–Summer Maize Cropping System

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Abstract: Soil degradation and high environmental costs impede agricultural production in North China. A 6-year field experiment was conducted to determine the effects of tillage practice and nitrogen application rate on changes in soil fertility and wheat yield. Four tillage systems (rotary tillage without maize straw return through 6 years, RT; rotary tillage with maize straw return through 6 years, RS; deep tillage with maize straw return through 6 years, DS; and rotary tillage through 2 years followed by deep tillage next year with maize straw applied for two cycles, RS/DS) and three N levels (HN, 300 kg N ha^{-1}, refers to traditional farming practice; MN, 0.75 × HN, 225 kg N ha^{-1}, to recommended N rate; and LN, 0.5 × HN, 150 kg N ha^{-1}, to reduced N rate) were tested. The soil organic carbon, labile organic carbon, inorganic N, available phosphorus, and available potassium under straw return treatments were significantly higher than RT in the 0–30 cm soil layer ($p < 0.05$). The microbial diversity, invertase, urease, and alkaline phosphatase activities also increased when maize straw was returned. Tillage practices could distribute maize straw in different depths of the soil and then affect soil nutrients, enzyme activity, and microbial diversity. The RS treatment presented the greatest effects in the 0–10 cm layer, while more significant impacts were observed in DS and RS/DS treatments at the 10–30 cm depths. The levels of soil nutrients and enzyme activity increased with an increased N rate. Compared to that under LN, wheat yields increased under HN and MN treatments, whereas there were no significant differences between HN and MN ($p > 0.05$). An increasing tendency of grain yield was observed in DS and RS/DS, while conversely so in RS. RS/DS had lower farm costs than DS during the study duration. Thus, RS/DS at 225 kg N ha^{-1} is the best method for improving soil fertility and wheat yield.

Keywords: tillage practice; nitrogen application rate; soil nutrient; soil microorganism; winter wheat

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1. Introduction

Traditional agriculture in the North China Plain often uses high fertilizer inputs to obtain high yields [1,2]. Excessive use of nitrogen (N) fertilizers has resulted in some environmental problems, including soil deterioration, water pollution, and fertility loss. The N lost to the atmosphere returns to the soil through atmospheric N deposition, causing ecological problems such as soil acidification, changes in the structure and function of soil microbial communities, and an increase in soil greenhouse gas emissions. Excess N in the soil is discharged into groundwater through leaching, resulting in groundwater pollution [3–5]. Therefore, determining agricultural methods for reducing environmental and farm costs and improving soil fertility while maintaining high crop yield is urgently required.

With the increase in population and the dramatic increase in the world's food production levels, the production of crop straw as a major agricultural by-product has been increasing yearly. Crop straw is abundant in organic matter holding carbon (C) and nutrients [6], and the application of crop straw to cultivated soil has favorable effects on soil characteristics [7–9]. Straw return has a role in the improvement of soil structure by reducing soil bulk and increasing soil porosity, while the improvement of soil structure contributes to the improvement of soil physical and biological processes. After straw return, as the decomposition process proceeds, cellulose, and hemicellulose are easily decomposed by microorganisms to produce small molecule organic acids for utilization, thus increasing soil organic matter content and microbial activity, facilitating soil aggregate formation, promoting soil N mineralization process, and reducing N leaching [10,11]. The abundance of N in straw and the application of N fertilizer contributed much more to soil N input than the N taken away by the crop, and the microorganisms also sequestered N when the straw was returned to the field, thus reducing N losses [12,13]. Therefore, crop straw may help replace a portion of the current chemical fertilizer rate. The addition of crop straw to a field may be a strategy to improve soil fertility and reduce chemical fertilizers inputs [14].

The concentrations of soil nutrients, i.e., inorganic nitrogen (IN), available phosphorus (AP), available potassium (AK), and soil organic carbon (SOC), are key factors contributing to improving soil fertility because of their beneficial effects on crop growth [15,16]. Specifically, improving the SOC content is favorable for maintaining the nutrient supply in soil and is related to more stable agricultural production systems [17,18]. Soil microorganisms play critical roles in the decomposition of residues and the biochemical recycling of soil nutrients in ecosystems, and microbial diversity is also essential to maintain the health and quality of soil [19]. Soil enzymes are synthesized and secreted by soil microorganisms, which then catalyze specific reactions in the recycling of nutrients and are potential indicators of soil fertility [20]. SOC can be supplemented by providing carbon input by returning crop residues to the field rather than burning or otherwise using them as waste or for other purposes [21–23]. Previous studies have also demonstrated that returning crop straw to fields improved the activity of soil enzymes [24] and increased microbial biomass [25,26]. Therefore, straw return could become an effective method for facilitating sustained nutrient input reductions, improving nutrient efficiency, and contributing to sustainable agriculture.

Straw incorporation is often implemented with soil cultivation in crop production. In the last decade, smallholders have extensively adopted rotary tillage in the North China Plain because it is labor saving and reduces costs [27]. Nevertheless, extensive rotary tillage deteriorates soil characteristics in the subsoil layer and ultimately decreases productivity, which is not beneficial from an ecological or production standpoint [28,29]. Conversely, deep plowing can create a more appropriate soil environment for root growth but with inevitably higher costs than rotary tillage [30–32].

Current research is centered on one type of soil tillage, i.e., deep tillage or rotary tillage, SOC level, soil structure, soil enzyme activity, or grain yield. The detailed changes in soil fertility and wheat yield under mixed tillage and N-fertilization conditions are largely unclear. Considering the current common tillage equipment, we hypothesized that rototilling through two years followed by deep tillage in the next year (RS/DS) would be an effective way to reduce agricultural costs and improve soil quality while maintaining high wheat yields. Therefore, this experiment was set: (1) to investigate the changes in wheat yield under different N and tillage regimes, (2) to study the effects of different N applications and tillage systems on soil properties and straw inputs in different soil layers, and the relationship between straw inputs and soil properties, and (3) to seek an optimized tillage assembly could maintain high yields with lower N fertilizer costs.

2. Materials and Methods

2.1. Experimental Site

A field experiment was conducted in 2015–2021 at the Dongping County Agricultural Science Research Institute, Tai'an, Shandong, China (35°90′ N, 116°37′ E). The soil was a sandy loam (Typic Cambisols; FAO/EC/ISRIC, 2003) (pH: 7.92). The primary soil properties in the 0–30 cm layer shown in Table 1.

Table 1. The basic soil properties in the 0–10, 10–20, and 20–30 cm layers before treatment.

Depth (cm)	SOC (g kg^{-1})	LOC (g kg^{-1})	IN (mg kg^{-1})	AP (mg kg^{-1})	AK (mg kg^{-1})
0–10	8.53	2.75	24.96	20.53	101.24
10–20	7.73	2.38	22.58	16.89	84.38
20–30	6.92	1.94	19.88	13.65	67.19

Note: SOC, soil organic carbon; LOC, labile soil organic carbon; IN, inorganic nitrogen; AP, available phosphorus; and AK, available potassium.

2.2. Experimental Design

The experiment was conducted during the winter wheat growing seasons and included three N rates (HN, 300 kg N ha^{-1}, refers to traditional farming practice; MN, 0.75 × HN, 225 kg N ha^{-1}, to recommended N rate; and LN, 0.5 × FP, 150 kg N ha^{-1}, to high efficiency as we anticipated) as main plots and four tillage systems (rotary tillage without maize straw return through 6 years, RT; rotary tillage with maize straw return through 6 years, RS; deep tillage with maize straw return through 6 years, DS; and rotary tillage through 2 years followed by deep tillage next year with maize straw applied for two cycles, RS/DS) as subplots. The treatments were arranged in a randomized block design with three replicates, and each subplot was 30.0 × 4.0 m. The winter wheat cultivar, Jimai 22, was used with a plant density of 2.25 × 10^6 plants ha^{-1} (equal spacing: 25 cm). In every growing season of winter wheat, 105 kg ha^{-1} P_2O_5 (as triple super phosphate) and 75 kg ha^{-1} K_2O (as potassium chloride) were applied as a preplant broadcast application along with half N (as urea) rate for the treatment. The remaining N fertilizer was furrow-applied at jointing stage.

After wheat harvest, straw was removed. Additionally, maize was planted with no tilling before planting. At maturity stage, thirty maize plants were acquired in the center of each plot to determine grain yield and dry matter of maize straw. After harvesting summer maize, land preparation was carried out. Table 2 shows the operational procedures for land preparation and the equipment used under different tillage methods. Planting of winter wheat started the day after land preparation.

Table 2. Operation procedures and the equipment used for different tillage practices.

Tillage	Operation Procedure
RT	Total maize straw removed from the field → Basal fertilizer spreading → Rotary cultivating two times with IGQN-200K-QY rotary cultivator [a] (working depth was about 10–12 cm) → Forming the border-check → seeding with common seeder
RS	Total maize straw returned to the field → Basal fertilizer spreading → Rotary cultivating two times with IGQN-200K-QY rotary cultivator (working depth was about 10–12 cm) → Forming the border-check → seeding with common seeder
DS	Total maize straw returned to the field → Basal fertilizer spreading → Mouldboard plowing once with ILFQ330 turnover plow [b] (working depth was about 25–30 cm) → Harrowing 2 times with 1BZ-3.0 disk harrow [c] → Forming the border-check → seeding with common seeder
RS/DS	The same to RS in the first two years → the same to DS in the 3rd season (two cycles in six years)

[a] The manufacturer of the IGQN-200K-QY rotary cultivator is YTO Group Corporation (Luoyang, China). [b] The manufacturer of the ILFQ330 turnover plough is Runlian scientific and technological development Co., Ltd. [c] The manufacturer of the 1BZ-3.0 disk harrow is Yucheng Hongri machinery manufacturing Co., Ltd.

2.3. Sampling

After the 6-year field experiment, soil samples were collected from 0–30 cm depths (10 cm per layer) within each experimental unit one day before wheat harvest (i.e., 12 June 2021). Within each experimental unit, a soil sample was collected with a soil tube (ETC-300E, Yitong, Changzhou, China) using a five-point sampling method. Five replicates were mixed into one sample. The soil sample was fully mixed and divided into three parts. One part was stored in a 4 °C refrigerator for the determination of soil enzyme activity and soil microbial diversity. One part was air dried and used for the determination of soil organic carbon (SOC) and labile organic carbon (LOC). The rest of the soil was frozen in a refrigerator at −40 °C for the determination of soil available nutrients.

2.4. Measurement

The SOC content was assayed by the $K_2Cr_2O_7$-H_2SO_4 digestion method [33]. After leaching by potassium chloride solution, soil inorganic N content (IN) was determined using the continuous flow analyzer (AA3; Bran + Luebbe Co., Norderstedt, Germany) method, and soil available phosphorus (AP) and available potassium (AK) using the methods described by Wei et al. (2015) [20]. The soil invertase (Inv), alkaline phosphatase (Alp), and urease (Ure) activities were determined using Tabatabai's method (1994) [34]. Soil microorganisms were measured by Novogen (Shanghai, China).

An area of 1 m^2 was randomly selected and the loose soil was recompacted to pre-cultivation to estimate the distribution of straw in the different soil layers. Each layer of removed soil was placed in a nylon mesh bag, rinsed, and the straw in it was screened for drying and weighed. At the wheat harvest, all plants covering a 10 m^2 area from each plot were used to determine yield (grain yield was weighed at 14% moisture content).

2.5. Statistical Analysis

A one-way ANOVA was conducted using SPSS 19.0 Statistical Package (SPSS Inc., Chicago, IL, USA) with the soil trait as the response variable and the treatment as the fixed factor. The correlation analysis used the trait as the response variable and then straw inputs as fixed factors in the model using SPSS 19.0 Statistical Package. Significance was determined using the LSD test. p-values < 0.05 were considered statistically significant. SigmaPlot 14.0 was used for preparing graphs.

3. Results

3.1. Cumulative Straw Inputs

Tillage method and nitrogen application led to significant differences in straw input. Over the 6-year experimental period, the total straw inputs in the RS, DS, and RS/DS treatment were 52.16–54.99 Mg ha^{-1}, 54.39–58.63 Mg ha^{-1}, and 54.23–58.23 Mg ha^{-1}, respectively. The number of straw inputs increased with increasing nitrogen application rate. Compared with MN and LN, the cumulative straw inputs under HN to the 0–30 cm soil layer increased by 2.39 Mg ha^{-1} and 11.07 Mg ha^{-1}, respectively. The straw input amounts in the different systems ranked as RS > RS/DS > DS in the 0–10 cm layer, in which the cumulative straw inputs under RS increased by 69.1% and 11.8%, respectively, compared to DS and RS/DS. In contrast, in the 20–30 cm soil layer, the cumulative straw inputs ranked as DS > RS/DS > RS, in which the cumulative straw inputs under DS and RS/DS increased by 474.6% and 159.6%, respectively, compared to RS (Table 3).

Table 3. The cumulative straw inputs (Mg ha^{-1}) in different soil layers.

Depth (cm)	HN			MN			LN		
	RS	DS	RS/DS	RS	DS	RS/DS	RS	DS	RS/DS
0–10	50.04 a	29.90 c	45.19 b	49.72 a	29.46 c	44.30 b	47.47 a	27.74 c	42.22 b
10–20	4.95 c	22.28 a	10.90 b	4.92 c	21.95 a	10.66 b	4.69 c	20.67 a	10.05 b
20–30	0.00 c	6.45 a	2.14 b	0.00 c	6.35 a	2.10 b	0.00 c	5.98 a	1.96 b

Note: Values in the same row and nitrogen treatment with the different letters are significantly different at $p < 0.05$.

3.2. Soil Organic Carbon

The tillage practice and N rate had a significant effect on SOC in the 20–30 cm layer. Only tillage practice significantly affected LOC at the three soil depths (Table 4). Straw return led to an increase in the SOC and LOC content in the 0–30 cm soil layers (Figure 1). Compared with no straw return, straw return increased SOC content by 15.5%, 15.1%, and 16.6% in the 0–10, 10–20, and 20–30 cm soil layers, and increased LOC content by 45.7%, 47.3%, and 63.2%, respectively. In the 0–10 cm soil layer, SOC content under RS increased by 4.7% and 1.6% on average compared with DS and RD/DS, respectively. Compared with DS and RD/DS, SOC content under RS significantly decreased by 7.0% and 5.4% in the 10–20 cm soil layer, and by 10.5% and 8.4% in the 20–30 cm soil layer, respectively. Similarly, soil LOC content in the 0–10 cm soil layer under RS increased compared with DS and RS/DS, but significantly reduced in the 10–30 cm soil layer. The average SOC content under MN and HN was 6.32% and 7.24% higher than that under LN, respectively; no differences were observed in the values between MN and HN (Figure 1).

Table 4. Variance analysis (*F* value) of soil nutrients content and enzymes activities in the 0–10, 10–20, and 20–30 cm soil layers.

Depth (cm)	Difference Source	SOC	LOC	IN	AP	AK	Inv	Ure	Alp
0–10	Nitrogen (N)	23.15 **	1.92 ns	60.28 **	11.52 **	8.60 *	56.33 **	18.19 **	84.66 **
	Tillage (T)	73.28 **	1102.07 **	22.95 **	139.49 **	14.92 **	10.51 **	6.91 *	33.65 **
	N × T	0.67 ns	0.20 ns	2.93 *	2.25 ns	2.78 ns	4.81 **	11.60 **	1.99 ns
10–20	Nitrogen (N)	19.93 **	0.39 ns	36.41 **	9.02 *	7.74 *	33.55 **	18.37 **	39.78 **
	Tillage (T)	79.87 **	126.87 **	32.58 **	129.81 **	27.73 **	27.00 **	18.70 **	33.84 **
	N × T	0.78 ns	0.73 ns	1.68 ns	1.62 ns	1.19 ns	6.30 **	4.22 **	3.83 **
20–30	Nitrogen (N)	6.43 **	0.01 ns	29.66 **	6.87 *	7.74 *	13.12 **	57.71 **	64.30 **
	Tillage (T)	22.65 **	204.28 **	42.22 **	88.65 **	27.73 **	8.15 *	40.32 **	51.85 **
	N × T	2.77 *	0.55 ns	1.27 ns	3.98 *	1.19 ns	35.67 **	2.00 ns	3.11 *

Note: SOC, soil organic carbon; LOC, labile organic carbon; IN, inorganic nitrogen; AP, available phosphorus; AK, available potassium; Inv, invertase; Ure, urease; Alp, alkaline phosphatase. * $p < 0.05$; ** $p < 0.01$; ns not significant.

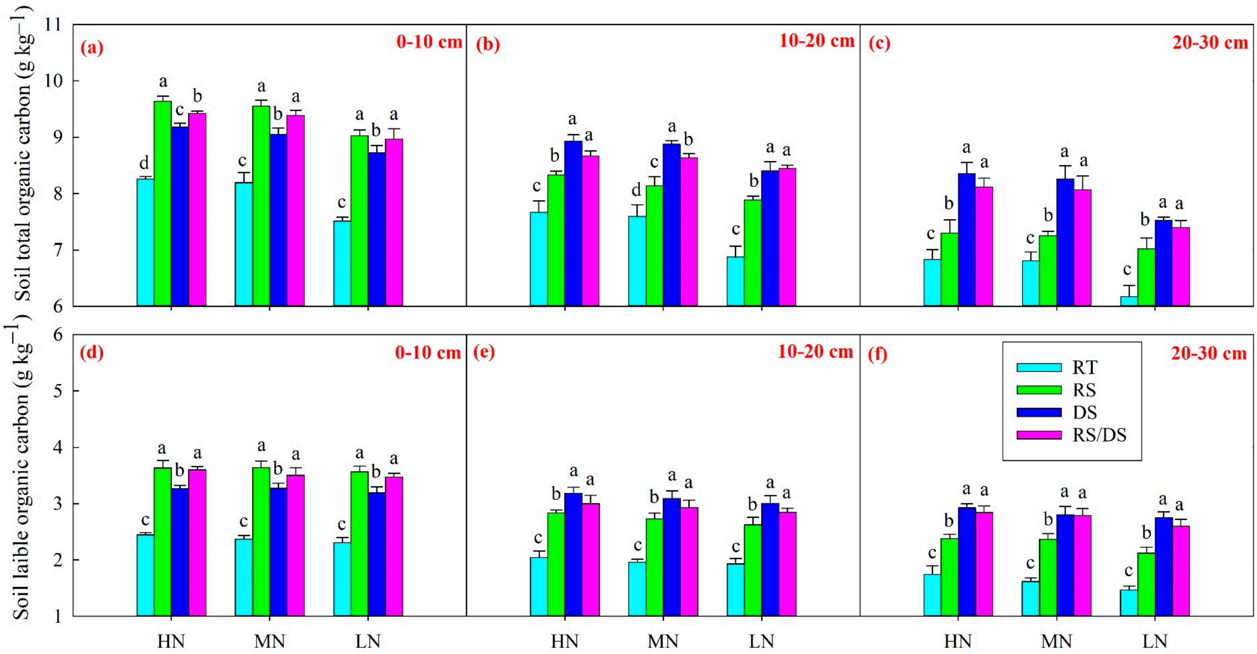

Figure 1. Content of SOC and LOC in the 0–30 cm soil layer under different treatments. The content values were the average readings for each treatment. Vertical bars represent ± standard error of the mean (*n* = 3) where they exceed the size of the symbol, and different lowercase letters indicate significant differences ($p < 0.05$).

3.3. Soil Nutrient

Both tillage practice and N rate treatment significantly affected IN, AP, and AK content at the three soil depths, and the interaction was significant for inorganic nitrogen and available phosphorus in the 0–10 and 20–30 cm soil layers, respectively, (Table 4). Compared with no straw return, straw return significantly increased IN content by 30.6%, 25.3%, and 41.1%, increased AP content by 29.4%, 33.5%, and 32.8%, and increased AK content by 25.0%, 23.9%, and 30.8% in the 0–10 cm, 10–20 cm, and 20–30 cm soil layers, respectively. In the 0–10 cm soil layer, IN content under RS and RS/DS increased by 7.7% and 4.9%, AP content increased by 12.1% and 8.8%, and AK content increased by 11.3% and 7.4%, compared with DS, respectively. However, compared with DS, IN content under RS and RS/DS decreased by 12.2% and 2.0%, AP content decreased by 10.0% and 2.9%, and AK content decreased by 11.3% and 2.0% in the 10–20 cm soil layer, respectively; and IN content decreased by 18.8% and 4.0%, AP content decreased by 14.1% and 2.5%, and AK content decreased by 12.2% and 1.8% in the 20–30 cm soil layer, respectively. Meanwhile, the IN, AP, and AK content increased with an increased N rate. Compared with LN, IN content under MN and HN increased by 21.6% and 30.1%, AP content increased by 8.0% and 10.2%, and AK content increased by 11.1% and 13.9%, respectively (Figure 2).

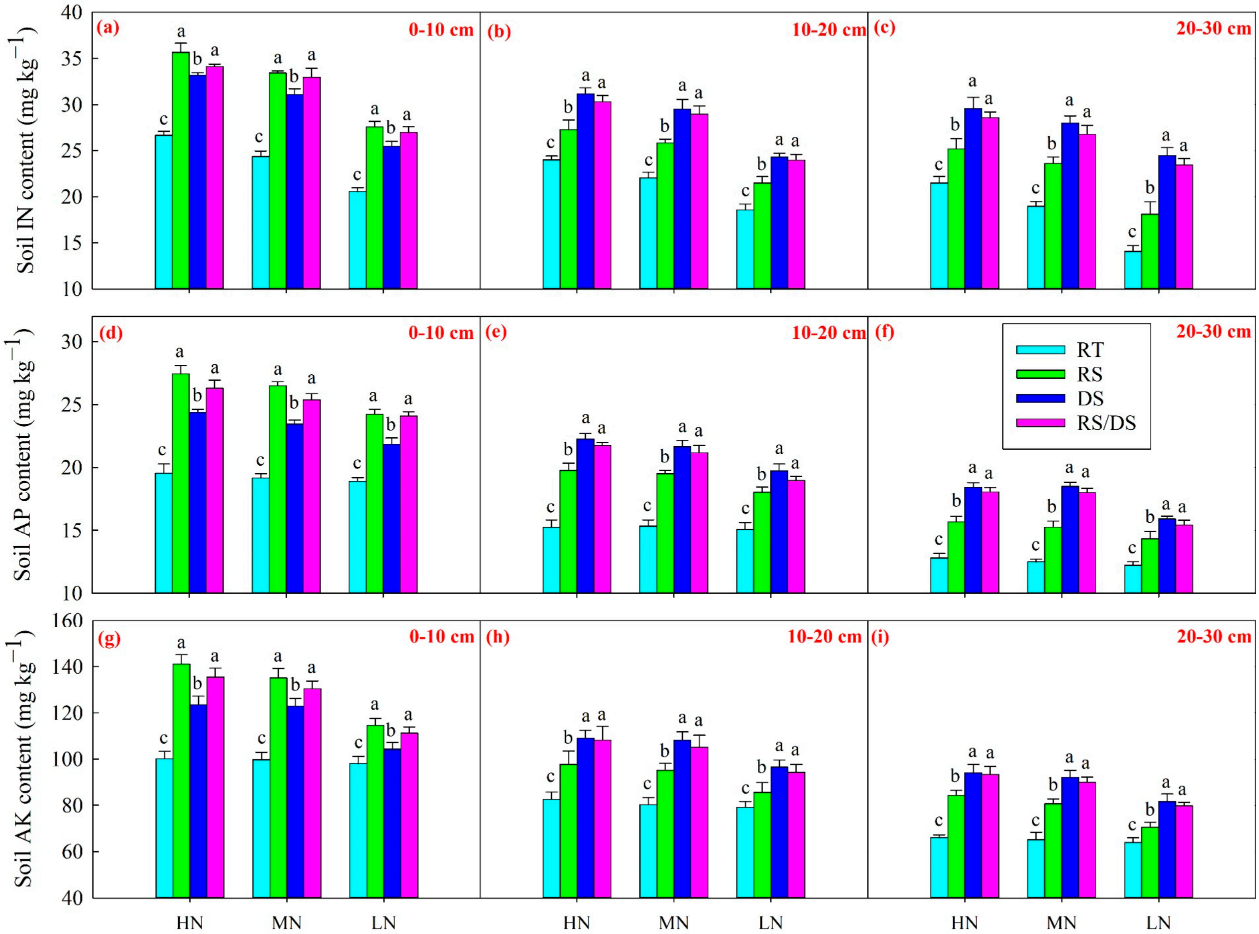

Figure 2. Soil inorganic nitrogen, soil available phosphorus, and soil available potassium under different tillage and nitrogen managements in the 0–30 cm soil layer. Values were the average readings for each treatment. Vertical bars represent ± standard error of the mean (n = 3) where they exceed the size of the symbol, and different lowercase letters indicate significant differences ($p < 0.05$).

3.4. Soil Enzyme Activities

Combined analysis of variance indicated that the effects of tillage practice and N rate were significant ($p < 0.01$) for Inv, Ure, and Alp activity at the three soil depths. Whereas their interaction was insignificant for Ure in the 20–30 cm layer and for Alp in the 0–10 cm layer, respectively, (Table 4). Compared to no straw return, straw return significantly increased the mean soil Inv, Ure, and Alp activity levels by 28.19%, 24.28%, and 22.59%, respectively, in the 0–30 cm layer (Figure 3). In the 0–10 cm soil layer under RS and RS/DS, soil Inv activity increased by 7.3% and 6.1%, Ure activity increased by 8.1% and 4.8%, and Alp activity increased by 9.5% and 7.2%, respectively. However, in the 10–20 cm soil layer under DS and RS/DS, soil Inv activity increased by 12.5% and 10.0%, Ure activity increased by 15.9% and 11.8%, and Alp activity increased by 12.9% and 10.9%, respectively, compared with RS; and in the 20–30 cm soil layer, the average increase in soil Inv activity was 16.5%

and 14.2%, Ure activity was 17.6% and 15.9%, and Alp activity was 15.5% and 12.3%. With N rate increasing, the soil Inv, Ure and Alp activity levels were significantly improved at the three soil depths, respectively. Compared with LN, Inv activity under MN and HN increased by 9.0% and 21.8%, Ure activity increased by 12.3% and 17.7%, and Alp activity increased by 19.1% and 28.9% in the 0–10 cm soil layer, respectively; and in the 10–20 cm soil layer, the average increase in soil Inv activity was 11.0% and 20.3%, Ure activity was 19.3% and 26.8%, and Alp activity was 18.5% and 25.5%; and the soil Inv activity increased by 5.9% and 18.0%, Ure activity increased by 21.2% and 35.5%, and Alp activity increased by 21.0% and 31.1% in the 20–30 cm soil layer.

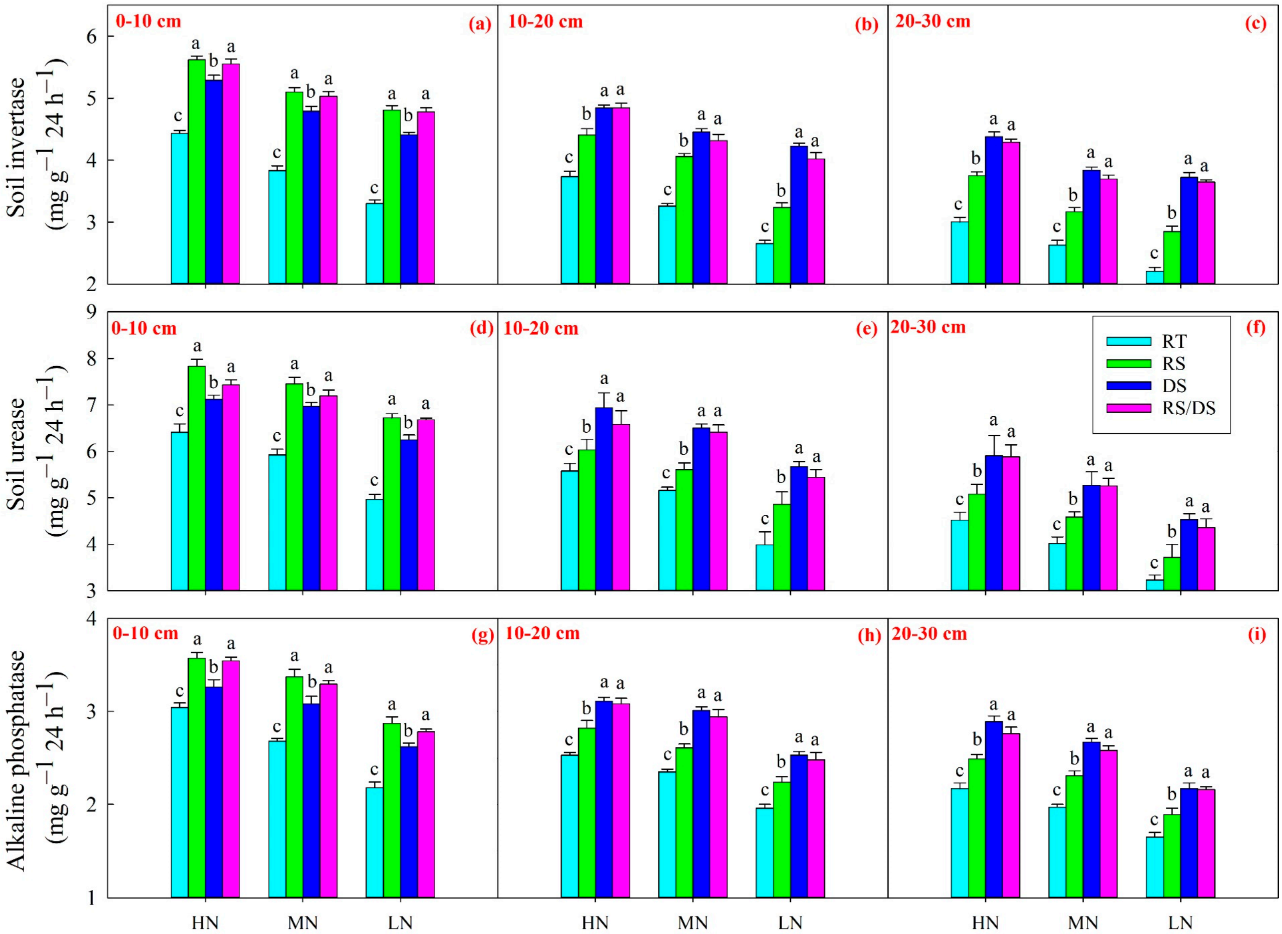

Figure 3. Soil enzymes activities in the 0–30 cm soil layer under different treatments. Inv, invertase; Ure, urease; Alp, alkaline phosphatase. The content values were the average readings for each treatment. Vertical bars represent ± standard error of the mean (n = 3) where they exceed the size of the symbol, and different lowercase letters indicate significant differences (p < 0.05).

3.5. Soil Microorganism

Tillage practice influenced microbial diversity at different soil depths (Figure 4). At the 0–10 cm soil depth, the microbial diversity (number of OTU) was ranked in the order: RS > RS/DS > DS > RT; the OTUs of RS, RS/DS, and DS were 51.43%, 22.89%, and 30.99% higher, respectively, than that of RT. However, in the 10–30 cm layers, microbial diversity was ranked in the order: DS > RS/DS > RS > RT, while the OTUs of RS, RS/DS, and DS were 30.29%, 68.47%, and 52.67% higher, respectively, than that of RT in the 10–20 cm layer and 26.23, 66.43, and 45.59% higher, respectively, than that of RT in the 20–30 cm layer.

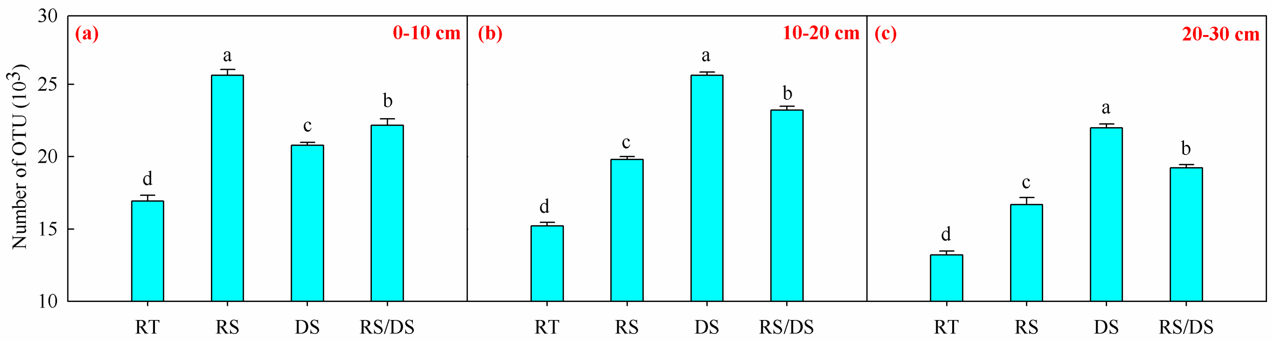

Figure 4. Soil microbial diversity in the 0–30 cm soil layers under MN treatment. The content values were the average readings for each treatment. Vertical bars represent ± standard error of the mean (n = 3) where they exceed the size of the symbol, and different lowercase letters indicate significant differences ($p < 0.05$).

3.6. Correlation Analysis

The correlation analysis between cumulative straw input and soil properties in different soil layers showed that: in the 0–20 cm layers, the cumulative straw input was positively and significantly correlated with SOC, LOC, IN, AP, AK, Inv, Ure, and Alp levels, respectively. In the 20–30 cm layer, the cumulative straw input was positively and significantly correlated with SOC, LOC, IN, AP, AK, and Inv levels, respectively; however, no significant correlations were found between the cumulative straw input and the levels of Ure and Alp activity (Table 5).

Table 5. Correlation analysis between cumulative straw inputs and soil properties in different soil layers.

Factors	0–10 cm		10–20 cm		20–30 cm	
	Regression Model	R^2	Regression Model	R^2	Regression Model	R^2
SOC	$y = 0.03x + 8.03$	0.83 **	$y = 0.07x + 7.72$	0.60 *	$y = 0.20x + 7.11$	0.46 *
LOC	$y = 0.03x + 2.42$	0.98 **	$y = 0.05x + 2.30$	0.66 **	$y = 0.15x + 2.13$	0.43 *
IN	$y = 0.20x + 24.03$	0.55 **	$y = 0.35x + 23.01$	0.39 *	$y = 1.26x + 21.57$	0.36 *
AP	$y = 0.16x + 19.17$	0.91 **	$y = 0.29x + 16.95$	0.59 **	$y = 0.67x + 14.55$	0.42 *
AK	$y = 0.74x + 98.79$	0.68 **	$y = 1.22x + 86.35$	0.58 **	$y = 3.07x + 75.36$	0.37 *
Inv	$y = 0.03x + 3.89$	0.68 **	$y = 0.05x + 3.69$	0.46 *	$y = 0.14x + 3.39$	0.38 *
Ure	$y = 0.04x + 5.78$	0.66 **	$y = 0.08x + 5.17$	0.43 *	$y = 0.18x + 4.41$	0.25 ^{ns}
Alp	$y = 0.02x + 2.61$	0.43 *	$y = 0.03x + 2.41$	0.38 *	$y = 0.09x + 2.17$	0.28 ^{ns}

Note: * and ** indicate significance at $p < 0.05$ and 0.01 levels, respectively. y, soil properties; x, the cumulative straw input at corresponding soil layer.

3.7. Grain Yield

Grain yields from straw return treatments were greater than those in RT (Table 6). In 2015–2016 and 2016–2017, there were no differences among treatments with straw return, but lower values were observed in RS, compared to DS and RS/DS. Under the RT and RS treatments, downward tendencies of grain yield were observed from the 3rd year, and the average grain yields in 2020–2021 were 8.31% and 7.36% lower than in 2015–2016, respectively. In contrast, there were continuously increasing tendencies of grain yield in DS and RS/DS during the study period. Grain yields under HN and MN treatments were higher than under LN treatment; the yield was 8.86% and 8.09% higher in 2015–2016, 9.91% and 8.85% higher in 2016–2017, 6.84% and 5.24% higher in 2017–2018, 6.74% and 5.91% higher in 2018–2019, 7.58% and 6.18% higher in 2019–2020, and 7.93% and 5.88% higher in 2020–2021, respectively. However, there were no significant differences between HN and MN (Table 6).

Table 6. Grain yields of winter wheat under different treatments from 2015 to 2021.

Nitrogen Rate	Tillage Method	Grain Yield (Mg ha^{-1})					
		2015/2016	2016/2017	2017/2018	2018/2019	2019/2020	2020/2021
HN	RT	7.91 b	8.07 b	7.62 c	7.53 c	7.48 b	7.36 b
	RS	8.53 a	8.55 a	8.09 b	7.98 b	7.83 b	7.71 b
	DS	8.33 a	8.61 a	8.70 a	8.82 a	8.99 a	9.08 a
	RS/DS	8.66 a	8.56 a	8.67 a	8.76 a	8.72 a	8.91 a
MN	RT	7.86 b	7.94 b	7.53 c	7.48 c	7.26 c	7.17 b
	RS	8.39 a	8.39 a	7.99 b	7.94 b	7.76 b	7.48 b
	DS	8.43 a	8.53 a	8.57 a	8.74 a	9.06 a	8.95 a
	RS/DS	8.46 a	8.45 a	8.71 a	8.85 a	8.96 a	8.83 a
LN	RT	7.38 b	7.31 b	7.09 c	7.02 c	6.85 c	6.61 c
	RS	7.75 a	7.84 a	7.77 b	7.72 b	7.56 b	7.28 b
	DS	7.91 a	7.96 a	8.30 a	8.35 a	8.41 a	8.39 a
	RS/DS	7.92 a	7.99 a	8.21 a	8.29 a	8.33 a	8.35 a

Note: Different lowercase letters represent significant differences between different tillage treatments at the same nitrogen application rate in the same growing season ($p < 0.05$).

4. Discussion

It was reported that straw return and N management were often directly related to the changes in agricultural soil nutrients [33,35]. Our present study indicated that straw return increased the levels of SOC, LOC, IN, AP, and AK concentration relative to RT, suggesting that straw return was beneficial for nutrient accumulation to improve future soil fertility. The applied straw could provide nutrition inputs, as well as improve soil condition in the tillage layer, promoting crop growth and more root biomass returning to the soil [36,37]. The SOC levels under MN and HN treatments differed from those under LN in that SOC increased as more root biomass was incorporated and decomposed [38,39]. There was no difference in SOC levels between MN and HN treatments, which suggested that excessive N was not necessary for SOC accumulation. The straw incorporation rate might be the main limiting factor determining the SOC levels [40]. The SOC level is determined by the difference between organic matter input to soil and organic matter lost through mineralization, erosion, and leaching. In this study, RS/DS and DS significantly enhanced soil SOC levels in the 10–30 cm soil layer compared to RS. In addition, although RS/DS significantly reduced straw inputs in the 10–30 cm soil layer compared to DS, there was no significant difference between SOC under RS/DS and DS. Previous studies have shown that less soil disturbance and organic material return can accelerate microaggregate formation in macroaggregates [41], thus promoting the fixation of SOC. Conservation tillage under RS/DS can reduce the destruction of macroaggregates while promoting the agglomeration of microaggregates into macroaggregates and reducing the rate of aggregates' turnover, thus contributing to the reduction of SOC mineralization [42] and effectively enhancing the C pool level in subsoil soils [43,44].

Many studies have shown that long-term straw return increased soil enzyme activity and microbial diversity [45]. These tendencies in the microbial diversity and enzyme activity levels were also similar to our result. These increases were probably attributed to the increase in microbial population and microbial activity due to enhanced support supply [46–48]. Straw return could increase soil C and N concentrations, which provide energy for microbial growth and consequent accumulation of soil enzymes [49,50]. However, these observations were inconsistent with Guo et al. (2008) [51], who found that soil protease activities increased with N in the range of 0–180 kg N ha^{-1} but decreased with further increases in N application. The contradictory findings might have been due to the different soil characteristics, climate, straw incorporation methods, and N-fertilizer rate [52]. Furthermore, the interaction between tillage practice and N management showed various effects on soil enzyme activities at the three soil depths. This might be due to different enzymes responding inconsistently to changes in soil conditions.

Compared to DS, RS and RS/DS resulted in greater soil fertility in the 0–10 cm layer, and this might be mainly because they distributed more straw in the 0–10 soil layer (Table 3). However, the straw under RS was significantly less than that under DS in the 10–30 cm soil layers. The vastly different distribution characteristics of returned straw under RS and DS might be the major factor leading to the diversities in vertical distribution of soil fertility factors [31]. Our study also showed that straw input was significantly correlated with soil nutrient content in each layer (Table 5). On the other hand, the differences in soil condition after deep plowing tillage or rotary tillage affected the rate of straw decomposition [53], thereby resulting in variability in the accumulation of soil nutrients and microbial biomass. Although straw input under RS/DS significantly reduced in the 10–20 and 20–30 cm layers compared to DS, there were no significant differences in soil properties between them, which might be due to the redistribution of soil properties induced by rotational tillage. Previous studies have shown that straw returning combined with rotary tillage increased soil urease, phosphatase, catalase, and β-glucosidase activities in the 0–10 cm soil layer [54], indicating that the mixing of surface soil and straw can enhance soil enzyme secretion, which is crucial for straw decomposition and straw nutrient reuse [55]. The deep tillage method of incorporating straw into deep soil mainly improves the enzyme activity of subsurface soil, which may accelerate the nutrient cycle of subsoil [56].

The straw application always showed positive effects on crop yields and soil productivity, which was attributed mainly to the improvements in soil fertility [57,58], and was consistent with our study. Additionally, we revealed no differences in the yields between MN and HN. It was indicated that the excessive N application exceeded the nutrient needs of the crop, and therefore, could not continuously increase the grain yield [59]. The interaction of year and straw management practices had a significant effect on yield, indicating that the increase in yield may increase with the increase of years of straw return, which may be attributed to the gradual improvement in soil properties [60,61]. Declining tendencies in grain yield were observed from 2013–2014 under RT and RS treatments, which were associated with poor soil structure and an imbalance in the distribution of soil nutrients in the plow layer caused by continuous rotary tillage [62]. Continuous straw return combined with rotary tillage reduces surface soil temperature and moisture and leads to compacting of subsurface soils and causes upward movement of the plow substratum, which prevents crop roots penetrating and seriously interferes with crop production [63,64]. Deep plowing to a depth of about 30 cm is an effective measure to alleviate soil compaction by breaking the soil plow bottom layer [65], and straw return combined with deep tillage can reduce subsurface soil bulk density and increase soil porosity, thus increasing subsoil soil water and fertilizer capacity [66]. Relatively stable and increasing grain yields were observed in DS and RS/DS within 6 years, suggesting that straw return with continuous or timely deep plowing might be beneficial for increasing crop productivity. The RS/DS treatment could improve soil fertility and more uniformly distribute residues and nutrients within the rooting zone, and rotary tillage can be more profitable than deep tillage because it reduces fuel consumption and work time. Thus, it is clear that RS/DS is a more economical and sustainable choice for long-term land use.

5. Conclusions

Increasing N rate could significantly increase soil available nutrient and enzyme activity. However, wheat yield did not enhance substantially with the application of more than 225 kg ha^{-1} N. By performing deep plowing instead of rotary tillage every two years, the application of 225 kg N ha^{-1} could maintain both high yields and high SOC levels. Although RS/DS produced a comparable wheat yield with DS in the 6-year experiment, RS/DS reduced the farming costs in the process of land preparation. Thus, our findings indicated that RS/DS at the 225 kg N ha^{-1} could be recommended as a comprehensive management strategy to promote both agricultural productivity and sustainability for winter wheat production.

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