Effects of Deep and Shallow Tillage with Straw Incorporation on Soil Organic Carbon, Total Nitrogen and Enzyme Activities in Northeast China

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Abstract: The characterization of soil physicochemical properties and the resulting soil enzyme activity changes are crucial for understanding the effects of various tillage and straw management techniques on crop grain yield. In 2018–2019, we conducted a field micro-plot experiment to determine the effects of tillage depth and straw management on the soil physicochemical properties, enzyme activity, and maize grain yield. Six treatments were employed, including straw removal (CK), straw mixed with (SM), and straw buried (SB) into the soil under tillage depths of 10 (D10) and 30 cm (D30). The results demonstrated that SM and SB significantly increased the soil nitrate (NO$_3^-$–N) content and decreased the ammonium (NH$_4^+$–N) content in the 0–20 cm soil layer in 2018 relative to CK. SM had greater soil urease (URE) and acid phosphatase (APH) activities in the 0–20 cm soil layer, and SB improved the soil APH activity at the 30–40 cm depth in both seasons. D30 obtained a lower penetration resistance in the 10–40 cm soil profile and higher soil organic carbon (SOC) and soil total nitrogen (STN) contents at the 30–40 cm soil depth relative to D10. The soil enzyme activity was positively related to the soil nutrient content and negatively related to the soil penetration resistance in the 0–20 cm soil layer, particularly in D30. Compared with CK, the grain yield was higher by 2.48–17.51% for SM and 7.48–24.46% for SB in 2018 and 2019, respectively. The structural equation model analysis suggested that the tillage depth mainly affected the soil penetration resistance (PR) and pH; however, straw management dominantly influenced the soil mineral N levels, leading to other soil property changes and crop production results. In conclusion, straw incorporation with deeper plow tillage might be an optimal straw return approach for soil quality improvement and sustainable maize production in northeast China.

Keywords: straw return; SOC; soil enzyme activity; grain yield

1. Introduction

Soil degradation is recognized as a severe 21st century issue worldwide in the global agroecosystem [1]. Increased soil degradation threatens agricultural production and the food supply for the growing human population in developing countries and areas [2,3]. The organic residues derived from crop straw are considered as the greatest source of soil organic matter in the agroecosystem [4]. It is critical to return crop residue into the soil to maintain soil quality. In past decades, large quantities
of crop straw were produced in China accompanied by constant increased crop yield, which was approximately 1.04 billion tons in 2015, accounting for one–third of the global production [5]. Thus, the government proposed returning crop straw to the field soil to practice conservation agriculture. Finding an efficient approach for straw return is an urgent issue to achieve the goal of improving soil quality [6].

Direct straw return to the soil has been regarded as an environment–friendly approach due to its positive effects on improving soil health and contributing to sustainable agricultural development [7]. Studies reported that straw return improved the soil aggregation and soil water–holding capacity [8–10], alleviated soil erosion and runoff [11], enhanced soil respiration and soil enzyme activity [12,13], and increased the soil organic matter (SOM) pool of topsoil in field experiments [14–17]. Straw return promoted the increase of soil microbial biomass and activity and altered the supply of soil nutrients [18,19]. However, crop straw return is generally accompanied by various tillage practices, which determine the location of the straw incorporated into the soil and the interactions, as well as the disturbance extent of the native soil [2]. Both straw management and tillage practices together affect the soil’s physical and chemical properties and nutrient recycling [20,21]. Thus, the responses of soil properties to straw management with various tillage approaches require further study in different research areas [22–24].

In terms of the following crop yield, the effects of straw return were inconclusive and were shown to vary with the climatic conditions and crop systems [25]. Christian et al. reported a lower wheat grain yield in a 7-year study obtained under straw return management in Europe [26]. However, another study showed that straw return increased the crop yield under a crop rotation system in Breton, while the positive effect of straw was found in both crop monoculture and rotation systems at Ellerslie [27]. For the effects of tillage practice on crop yield under straw return cases, Brennan et al. suggested that plow tillage with straw incorporation presented more increasing grain yield than rotary tillage conditions [28], while You et al. reported the opposite results [29]. Additionally, Hu et al. found that there was no significant difference of grain yield between the above tillage methods with straw return [30]. Thus, it is necessary to fully clarify how tillage and straw management influence the following crop production via changing the soil’s physical and chemical properties in the field.

Northeastern China is one of the gold–belt regions for maize production in the world, where the total maize yield accounts for approximately 30.0% of the nation’s production [31]. Maize straw production in this area was nearly 72.3 million tons, accounting for 36.3% of the national straw yield in 2014 [5]. Considering that the surface retention with no–till systems is associated with low decay rates due to the low average temperature and low precipitation conditions, most farmers prefer to incorporate maize straw into soil with shallow rotary tillage (10–15 cm depth) in this area, and some of them practice deep plow tillage (25–30 cm depth) to return straw [3]. A comprehensive knowledge of the effects of different tillage and straw managements on soil properties, maize yield, and their interactions in this typical area is of great importance. Therefore, some novel understandings are needed of how shallow and deep straw return with rotary or plow tillage influence soil property changes, then affect crop grain yield. The objectives of the present study are to (1) explore the effect of tillage depths with and without straw return on the soil’s physical and chemical properties and enzyme activity, (2) compare the responses of maize grain yield to the combined effects of straw return with shallow and deep tillage, and (3) identify how tillage with and without straw return influences the maize yield via regulating the soil properties.

2. Materials and Methods

2.1. Site Description

This study was conducted in 2018 and 2019 at the Experimental Station of Shenyang Agricultural University, Shenyang, Liaoning province, China (41°82′ N, 123°56′ E; 43 m above sea level). The climate in this area is a warm-temperate continental climate. The cumulative precipitation values during
2018 and 2019 were 430.4 and 711.2 mm, respectively, during the growing period (Figure 1). The precipitation in 2018 was lower than the 15-year average precipitation of 507.2 mm during the growing period [29], indicating that there was poor rainfall. The mean monthly temperature was approximately 22.3 °C. The soil is classified as Hapli–Udic Cambisol (FAO Classification). Before this study, soil physicochemical properties at the 0–20 cm depth were: 10.8 g kg\(^{-1}\) soil organic carbon, 0.9 g kg\(^{-1}\) total N, 51.2 mg kg\(^{-1}\) available phosphorus (Olsen–P), 128.5 mg kg\(^{-1}\) available potassium (exchangeable K), and 1.4 g cm\(^{-3}\) soil bulk density (core ring method). Spring maize (Zea mays L.) is the primary crop with one harvest each year in this region.

Figure 1. The monthly precipitation (mm) and 10 day average air temperature (°C) from May 2018 to September 2019.

2.2. Experiment Design and Crop Management

The experiment was performed with a randomized complete blocks design employing two factors (tillage depth, T; and straw management, S) with three replicates. A total of six treatments were included: straw removal (CK) with tillage soil at the depths of 10 and 30 cm (D10 and D30), straw mixed (SM) with soil at the depths of 10 and 30 cm (D10 and D30), and buried (SB) into soil at the depths of 10 and 30 cm (D10 and D30). Micro–plots made using stainless–steel plates (length, width, and height of 1.5 × 1.2 × 0.7 m) without bottoms were employed in this study, and undisturbed soil was kept in the micro–plots. Similar previous crop (maize) yields were obtained from our study units in 2017, so that the effects of underground biomass of the previous crop could be negligible. In each study year, the previous crop residue would be cleaned completely before straw incorporation conducted. The maize straw, approximately 1.8 kg (corresponding to 10,000 kg ha\(^{-1}\), dry weight) for each plot, was chopped into 3–5 cm pieces and then manually returned into the soil with tillage practices around 15 to 20 days after the harvest in each study year. The SM and SB treatments were the equivalent of straw return by rotary tillage and plow tillage in the field, respectively.

Spring maize (ZD 958) was planted in early May, harvested at the end of September in each year, 12 plants (corresponding to 67,500 pl ha\(^{-1}\)) were kept for each plot after thinning, four border rows were arranged at each side of the experimental area as buffer zones in the field. Basal fertilizer with 75 kg N ha\(^{-1}\) (urea), 90 kg P\(_2\)O\(_5\) ha\(^{-1}\) (superphosphate), and 90 kg K\(_2\)O ha\(^{-1}\) (potassium chloride) was used when the maize was sown, and 150 kg N ha\(^{-1}\) (urea) was applied at the jointing stage of maize. The management practices for controlling pests, disease, and weeds were according to local practices for high–yield production.

2.3. Sampling and Measurements

Soil cores (5 cm internal diameter) were randomly taken at 10 cm increments to the depth of 40 cm from three random locations in each plot after harvest. A portion of each soil sample was air–dried for
the soil property analysis. Subsamples were passed through a 2 mm sieve and stored at 4 °C for the enzyme activity determination.

The soil pH was determined in a soil:water ratio of 1:2.5, and recorded with a PHSJ–3F digital pH meter. The penetration resistance (PR) of the soil was measured using hand compactness measurements (SC900, Field Scout, USA) from three different locations in each plot. The soil organic carbon (SOC) and total nitrogen (STN) were determined using an elemental analyzer (EA 3000, Italy). The nitrate (NO$_3^-$–N) and ammonium (NH$_4^+$–N) were extracted with 2 M KCl for 1 h and determined colorimetrically using an auto discrete analyzer (Smart Chem 200, France) according to Joseph and Henry (2008) [32].

The soil invertase (INV) activity was determined by incubating 5 g of soil with 15 mL of 8% sucrose solution at 37 °C for 24 h. The suspension reacted with 3,5-dinitrosalicylic acid, and we measured the absorbance at 508 nm [33]. The soil urease (URE) activity was determined by incubating 10 g of soil with 10 mL of 10% urea solution for 24 h at 37 °C. The formation of ammonium was measured spectrophotometrically at 578 nm [33]. We determined the soil acid phosphatase (APH) activity using a modified method adopted from [34].

The grain yield of maize was determined by harvesting all ears of each plot. The grains were separated from the air-dried cob manually. The moisture content of the grains was determined with a professional grain moisture measuring instrument (K.T.PM–8188–A, Japan). Finally, the grain yield was standardized to 14% of the moisture content.

2.4. Statistical Analysis

The effects of tillage depth, straw management, and their interactions on the soil physicochemical properties, enzyme activities, and grain yield were analyzed using two-way repeated measures analysis of variance (ANOVA) with SPSS 23.0 (SPSS Inc., Chicago, IL, USA). Duncan’s multiple range test was used to identify significant differences between treatments at $p < 0.05$. Correlations among the soil properties and enzyme activities were determined using redundancy analysis (RDA). The RDA was performed using the CANOCO 4.5 software package (Microcomputer Power, Ithaca, NY, USA). Origin 9.1 (Originlab, Northampton, MA, USA) was used to draw the figures.

A structural equation model (SEM) was constructed to explore the direct and indirect impacts of the soil physicochemical properties and enzyme activities on the maize grain yield. The model was based on a multivariate approach using AMOS software (IBM SPSS AMOS 22.0). There were 12 predictors in the model: tillage depth and straw management; pH; PR; NH$_4^+$–N, NO$_3^-$–N, SOC, and TN contents; and INV, URE, and APH activities in the 0–40 cm soil profiles, as well as grain yield. The model fitting was assessed using the Chi-square statistic and its associated $p$-value, comparative fitting index (CFI), goodness–of–fit (GFI), and root mean square error of approximation (RMSEA).

3. Results

3.1. Soil Physicochemical Properties and Enzyme Activity

In terms of the soil penetration resistance (PR) and pH, the ANOVA results demonstrated that the tillage depth demonstrated significant differences in the PR, but the tillage depth and straw treatments were found with completely opposite trends for the soil pH, as well as their interaction effects on the PR and soil pH in both seasons (Table 1). Under the D10 treatments, compared with the CK treatment, the soil pH at the 0–10 cm depth was decreased under the SM treatment in 2018, and the soil PR in the 10–20 cm layer was increased under the SB treatment in 2019 (Table 2). Under the D30 treatments, both the soil pH at 0–10 cm depth and PR in the 10–40 cm soil profile were reduced under SM treatment in 2019, compared with the CK treatment. Overall, the soil PR at the 10–40 cm depth in both seasons was higher under the D10 condition than that under the D30 treatment. The D30 treatment enhanced the soil pH at the 10–20 cm depth in 2018 and decreased it in the 20–30 cm soil layer in 2019, when compared with the D10 treatment.
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Table 1. ANOVA of the tillage depth and straw management effects on the soil’s physical and chemical properties, enzyme activity at the 0–40 cm depth, and maize grain yield (\(F\)-value).

| Year | Soil Properties | Tillage Depth (T) | Straw Management (S) | T×S |
|------|-----------------|-------------------|----------------------|-----|
| 2018 | Penetration resistance | 142.6 *** | 0.1 ns | 2.4 ns |
|      | pH | 368.2 *** | 0.7 ns | 11.2 *** |
|      | Ammonium | 71.5 *** | 204.1 *** | 15.2 *** |
|      | Nitrate | 126.9 *** | 583.3 *** | 76.4 *** |
|      | Soil organic carbon | 4.8 * | 0.7 ns | 12.8 *** |
|      | Total nitrogen | 1.1 ns | 0.1 ns | 5.0 * |
|      | Invertase | 589.8 *** | 258.4 *** | 44.3 *** |
|      | Urease | 0.1 ns | 55.1 *** | 0.9 ns |
|      | Acid phosphatase | 121.3 *** | 44.9 *** | 4.2 * |
|      | Grain yield | 3.3 ns | 6.8 * | 0.3 ns |
| 2019 | Penetration resistance | 63.7 *** | 12.7 *** | 22.0 *** |
|      | pH | 1.8 ns | 3.7 * | 0.1 ns |
|      | Ammonium | 147.5 *** | 211.6 *** | 188.8 *** |
|      | Nitrate | 399.4 *** | 440.5 *** | 567.3 *** |
|      | Soil organic carbon | 6.5 * | 10.6 *** | 1.6 ** |
|      | Total nitrogen | 2.6 * | 7.9 ** | 1.0 ns |
|      | Invertase | 152.9 *** | 168.5 *** | 112.5 *** |
|      | Urease | 0.3 ns | 4.7 * | 15.5 *** |
|      | Acid phosphatase | 54.1 *** | 38.0 *** | 6.4 ** |
|      | Grain yield | 0.1 ns | 2.5 ns | 0.1 ns |

ns: not–significant difference; *, ** and *** indicate significant differences between treatments at \(p < 0.05\), \(p < 0.01\), and \(p < 0.01\), respectively.

Table 2. The soil penetration resistance and soil pH at the 0–40 cm depth under tillage and straw treatments.

| Year | Treatment | Soil Penetration Resistance, KPa | Soil pH |
|------|-----------|----------------------------------|--------|
|      |           | 0–10 cm  | 10–20 cm | 20–30 cm | 30–40 cm |
|      |           | 0–10 cm  | 10–20 cm | 20–30 cm | 30–40 cm |
| 2018 | D10       | CK 277.5a | 589.3a | 689.3a | 659.5a | 5.7a | 5.2b | 5.6a | 5.9a |
|      |           | SM 267.5b | 690.5a | 739.9a | 680.2a | 5.2b | 5.2b | 5.7a | 6.0a |
|      |           | SB 312.7ab | 654.8a | 640.1a | 579.2ab | 5.2b | 5.2b | 5.8a | 5.8a |
|      | D30       | CK 348.3ab | 267.7b | 322.8b | 533.8ab | 5.7a | 5.1b | 5.8a | 5.8a |
|      |           | SM 279.4ab | 252.8b | 264.3b | 533.2ab | 5.7a | 5.7a | 5.7a | 6.0a |
|      |           | SB 371.1a | 322.9b | 269.9b | 496.5b | 5.6a | 5.6a | 5.8a | 6.0a |
| 2019 | D10       | CK 240.7a | 450.5b | 579.1b | 580.2ab | 5.8a | 6.2a | 6.4ab | 6.8a |
|      |           | SM 227.0ab | 487.1b | 631.9ab | 644.5a | 5.7a | 5.9a | 6.4ab | 6.5a |
|      |           | SB 210.5ab | 677.7a | 705.4a | 651.4a | 5.6a | 6.1a | 6.6a | 6.8a |
|      | D30       | CK 195.8ab | 329.7c | 419.3c | 543.4b | 5.9a | 6.1a | 6.2b | 6.7a |
|      |           | SM 138.4ab | 296.4c | 364.0c | 501.0b | 5.8a | 6.0a | 6.2b | 6.6a |
|      |           | SB 104.7b | 193.1d | 260.8d | 410.3c | 5.8a | 6.0a | 6.2b | 6.6a |

Different letters indicate comparisons with significant difference (\(p < 0.05\)) between treatments. Straw was removed (CK), mixed (SM) with, and buried into the soil (SB), and tillage was performed in 10 cm (D10) and 30 cm (D30) soil layers.

In both years, the soil ammonium (NH\(_4\)+–N) and nitrate (NO\(_3\)−–N) contents were significantly influenced by the tillage depth, straw management, and their interaction effects (Table 1). Under the D10 treatments, the soil NO\(_3\)−–N content in the 0–40 cm soil profile was increased under the SM and SB treatments in 2018, compared with the CK treatment. The soil NO\(_3\)−–N content in the 0–10 cm and 20–30 cm soil layers was also improved under SM treatment in 2019 (Figure 2). However, the soil NH\(_4\)+–N content in the 0–10 cm and 20–30 cm soil layers was improved by CK treatment, compared with other treatments. Under the D30 treatments, the soil NO\(_3\)−–N content in the 0–40 cm soil profile was higher under the SM and SB treatments in 2018 than under the CK treatment. The soil NO\(_3\)−–N content in the 30–40 cm soil layer was also enhanced by the SB treatment in 2019, the soil NH\(_4\)+–N content at the 10–20 cm soil depth was decreased by the SB treatment for the two years, and the soil NH\(_4\)+–N content in the 10–40 cm soil profile was reduced by SM treatment in 2018, while the opposite trend was observed in the 0–20 cm soil layers in 2019. Overall, the soil NO\(_3\)−–N content in the 20–40 cm soil
layers and NH$_4^+$–N content at the 0–10 cm soil depth were higher under the D30 treatment than those under the D10 treatment in both seasons.

Figure 2. The soil nitrate (NO$_3^-$–N) and ammonium (NH$_4^+$–N) contents at 0–40 cm depths under tillage and straw treatments. Values shown are the mean ± standard deviation (n = 3). Different letters indicate significant differences (p < 0.05) between treatments per 10 cm soil layer. Straw was removed (CK), mixed (SM) with, and buried (SB) into soil, and tillage was performed at 10 cm (D10) and 30 cm (D30) soil depths.

For the soil organic carbon (SOC) and total nitrogen (STN) contents, the tillage depth significantly affected the SOC in both seasons; however, straw management exhibited significant effects on the soil SOC and STN contents only in 2019 (Table 1). We observed clear variations in the SOC and STN contents between the D10 and D30 treatments in the 0–10 cm and 30–40 cm soil layers in both years. In particular, higher SOC and STN contents in the 0–10 cm layer were found under both the SM and SB treatments relative to the CK treatments, and similar results were also obtained in the 30–40 cm layer under the SB treatment (Figure 3). Neither SOC nor STN was greatly altered in the 10–20 cm and 20–30 cm soil layers between the D10 and D30 treatments in both seasons; however, with the D10 treatment at 10–20 cm, both of them were found with significantly higher values under the SM and SB treatments relative to the CK treatment.

The soil urease (URE) activity was significantly influenced by straw management, and the soil invertase (INV) and acid phosphatase (APH) activities were significantly affected by both the tillage depth and straw management, as well as their interaction effects in both years (Table 1). Under the D10 treatment, the soil INV, URE, and APH activities at the 0–10 cm depth and URE activity at the 30–40 cm depth were increased by the SM treatment. The soil INV and APH activities at the 10–20 cm depth were improved by the SB treatment in 2018 and 2019, and the soil URE activity in the 10–20 cm layer was increased by both the SM and SB treatments in 2018, compared with the CK treatment (Figure 4). Under the D30 treatments, the soil INV and APH activities in the 10–20 cm layer were higher under the SM treatment, and the soil INV activity in the 10–20 cm and 30–40 cm layers and APH activity in the 30–40 cm layer were greater under SB treatment in 2018 and 2019 than those under CK treatment (Figure 4). Overall, the soil INV and APH activities in the 0–10 cm layer were greater under the D10
treatment than those under D30 treatment, but higher INV and APH activities in the 20–40 cm layers were obtained from the D30 treatment than those from D10 treatment in both seasons.

**Figure 3.** The soil organic carbon (SOC) and total nitrogen (STN) contents at 0–40 cm depths under tillage and straw treatments. Values shown are the mean ± standard deviation (n = 3). Different letters indicate significant differences (p < 0.05) between treatments per 10 cm soil layer. Straw was removed (CK), mixed (SM) with, and buried (SB) into soil, and tillage was performed at 10 cm (D10) and 30 cm (D30) soil depths.

**Figure 4.** The soil invertase, urease, and acid phosphatase activity at 0–40 cm depths under tillage and straw treatments. Values shown are the mean ± standard deviation (n = 3). Different letters indicate significant differences (p < 0.05) between treatments per 10 cm soil layer. Straw was removed (CK), mixed (SM) with, and buried (SB) into soil, and tillage was performed at 10 cm (D10) and 30 cm (D30) soil depths.
3.2. Relationships between Soil Enzyme Activity and Soil Properties

According to the RDA results, the activities of the soil INV, URE, and APH were positively related to the soil NH$_4^+$–N, NO$_3^-$–N, SOC, and STN contents, and negatively related to the soil PR in both study years (Figure 5). The enzyme activities were also negatively related to the soil pH in 2019. According to the quadrant distribution of treatments within 0–40 cm soil layers, treatments were positively related to the soil nutrients (SOC, STN, NH$_4^+$–N, and NO$_3^-$–N) and enzyme activity (INV, URE, and APH) in the 0–10 cm and 10–20 cm soil layers, but negatively in the 20–30 cm and 30–40 cm soil layers, especially for D10 treatments.

3.3. Grain Yield

The maize grain yield was significantly influenced by straw management in 2018, but there was no significant difference found between treatments in 2019 (Table 1). However, the highest grain yield of maize in both seasons was observed from the SB treatments under either the D10 or D30 tillage depth, followed by the SM and CK straw treatments. Compared with the CK treatment, the grain yield was improved by the SM and SB treatments by an average of 20.99% (D10) and 15.90% (D30) in 2018, and 5.31% (D10) and 6.20% (D30) in 2019 (Figure 6).

3.4. Impacts of the Tillage Depth and Straw Management Induced Factors on the Maize Grain Yield

A structural equation model (SEM) was used to analyze the direct and indirect effects of the soil physical and chemical properties as well as the enzyme activity on the maize grain yield (Figure 7). The total variation in the maize grain yield was shown to be 58% by SEM analysis ($p = 0.272$, CFI = 0.994, GFI = 0.999, and RMSEA = 0.045). Among those drivers, the soil APH and URE activities were found to directly contribute to the grain yield of maize with a positive and a negative relationship, respectively. The soil physicochemical properties were involved with the maize grain yield through mediating the soil enzyme activities. For instance, the SOC and NO$_3^-$–N contents were found with a positive effect on the APH activity, while the soil NO$_3^-$–N content and pH were observed with a positive and negative effect on the URE activity, respectively. The STN content and PR presented a negative effect on the INV activity, which further affected the APH activity. Simultaneously, the tillage depth influenced the maize grain yield directly through the soil pH and PR, while straw management influenced the yield through the soil NO$_3^-$–N and NH$_4^+$–N contents.
Figure 6. The responses of the maize grain yield to tillage and straw treatments in 2018–2019. Box plots indicate the 25th, 50th, and 75th percentiles; the 25th percentile was obtained from the average of the minimum and medium values, the 75th percentile was obtained from the average of the maximum and medium values, the whiskers demonstrate the 10th, 90th percentiles, the “-”s represent the maximum and minimum percentiles, the “□”s show the mean values. Different letters indicate significant differences ($p < 0.05$) between treatments in each year. Straw was removed (CK), mixed (SM) with, and buried (SB) into soil, and tillage was performed at 10 cm (D10) and 30 cm (D30) soil depths.

Figure 7. The structural equation model showing the underlying relationships of tillage depth and straw management related to the maize grain yield during the study years ($\chi^2 = 5.152$, df = 4, $p = 0.272$, comparative fitting index (CFI) = 0.994, goodness-of-fit (GFI) = 0.999, and root mean square error of approximation (RMSEA) = 0.045). Continuous and dashed arrows indicate positive ($p < 0.05$) and negative ($p < 0.05$) relationships, respectively. Numbers (standardized path coefficients) on the arrows that follow the included variables show the explained percentage of variance by the predictors. The width of the arrows indicates the strength of the standardized path coefficient. The soil penetration resistance (PR); soil ammonium (NH$_4^+$–N) and nitrate (NO$_3^-$–N) contents; soil organic carbon (SOC); soil total nitrogen (STN); and soil invertase (INV), urease (URE) and acid phosphatase (APH) activity at the 0–40 cm depths at post–harvest of maize.
4. Discussion

4.1. Responses of the Soil Physicochemical Properties and Enzyme Activity to Tillage and Straw Management

The changes to soil nutrient content resulted in the transformation of soil quality and were defined as the indicators for sustainable agriculture productivity [35]. Chen et al. reported that rotary and plow tillage with straw incorporation management significantly increased the soil NH\textsubscript{4}+–N and NO\textsubscript{3}–N contents in the 0–30 cm layers, which was also demonstrated in the current study for the NO\textsubscript{3}–N content influenced by the D10 and D30 tillage treatments [36]. Relative to the CK treatment, both the SM and SB treatments enhanced the soil NO\textsubscript{3}–N content in the 0–40 cm layer, but decreased the soil NH\textsubscript{4}+–N content in the 0–20 cm soil layer in 2018 (Figure 2). These results indicated that straw return might improve the activity of nitrifying bacteria and archaea, promote the nitrification process, and thus rapidly convert NH\textsubscript{4}+ into NO\textsubscript{3}–, contributing to the above phenomenon [37], which was suggested from the SEM results showing that the soil NH\textsubscript{4}+–N and NO\textsubscript{3}–N contents were directly regulated by straw managements, as well (Figure 7). Deep tillage (D30) was shown to break the plow pan layers and reduce the penetration resistance and improve rainfall interception and soil nutrient cycling [9,23,24], thus resulting in the soil NO\textsubscript{3}–N content increasing in the 20–40 cm layers, relative to those under D10 treatments (Figure 3). The NO\textsubscript{3}–N content under SM + D10 was significantly greater than those under other treatments in the 0–10 cm soil layer, while soil NO\textsubscript{3}–N content under SB + D30 was significantly higher in the 30–40 cm layer. It was generally accepted that rotary tillage with straw incorporation accelerated the straw decomposition and nutrient cycling in the surface soil layer [22], and the favorable soil porosity under plow tillage with straw incorporation promoted NO\textsubscript{3}–N leaching to the bottom of the soil profile [38].

Previous research indicated that shallow tillage significantly increased the SOC and STN contents in the surface layer, relative to deep tillage [16]. These results were consistent with the findings from our studies regarding D10 straw management (Figure 3). This may be due to shallow tillage promoting the development of the root in the surface layer and properly supplying more root–carbon into the soil [39]. However, the SOC and STN contents were further enhanced under straw return management within the D10 condition, compared to those under the CK treatment in this study (Figure 3). This might be explained in that the straw return improved the soil microbial biomass and accelerated the straw decomposition and soil organic matter immobilization in the surface soil layer [15,40]. In turn, deep tillage remarkably increased the SOC and STN contents in the subsoil layer (30–40 cm). On the one hand, deep tillage transfer surface soil with higher SOC in the bottom layer led to the homogenization of SOC and STN across the whole tillage layer, thus contributing to the increased SOC and STN in the subsoil layer [41]. On the other hand, the favorable soil ventilation condition and broken plow pan layers promoted the root development in the subsoil layer and increased the root–carbon input, as well [9].

Soil enzymes, as indicators of soil health, played a unique role in the soil nutrient cycling of agroecosystems [13]. Previous studies reported the effect of shallow tillage on increasing soil enzyme activities at the 0–10 cm depth, such as β–glucosidase, URE, and phosphatase and catalase activities [42]. Significant improvements in the soil INV, URE, and APH activities were observed in D10 treatments from the current study (Figure 4), suggesting that shallow tillage depth could affect more soil enzyme activities than deep depths. More importantly, the highest soil enzyme activities were found in the surface layer under SM + D10, indicating that straw incorporated with surface soil can enhance soil enzyme secretions, which is critical for straw decomposition and soil nutrient cycling [43].

However, deep tillage (D30) improved the soil enzyme activities in the 20–40 cm soil layers, and greater soil INV and APH activities in the 30–40 cm soil layer were obtained from the SB + D30 treatment. These results revealed that plow tillage with straw incorporation into the deep soil layer might accelerate the nutrient cycling of the subsoil layer due to increased soil enzyme activities [36]. Our study suggested that the activities of these soil enzymes were significantly correlated with the soil physicochemical properties, particularly at the 0–20 cm soil depth (Figure 5). Higher enzyme
activities corresponded to increased soil nutrient contents, which were likely due to their positive feedback of stimulating the synthesis of these enzymes under straw input conditions [42]. In parallel, the relationship between soil enzyme activities and PR was presented with a negative direction (Figure 5). This suggested that tillage and straw return practices affected the soil structure and further regulated the soil enzyme activities. Additionally, there was a significant negative correlation between the soil enzyme activities and soil pH, which was proven in a previous study, concluding that straw return altered the soil pH to an extent [44].

4.2. Maize Grain Yield Affected by Tillage and Straw Managements

The straw return was an effective measure to improve the soil structure and nutrient contents to achieve higher crop yields [45]. The results of this study showed that SB treatment exhibited the improvement tendency of the grain yield of maize in both study years, relative to the CK treatment, particularly in 2018 with lower rainfall (Figures 1 and 6). The grain yield increment under the condition with straw buried into the soil was, in part, realized by forming a straw layer beneath the tillage layer as a result of the decreased soil penetration resistance and enhanced water-holding capacity of the tillage layer [9,46], and this was beneficial for the crop growth and root distribution in the deep soil layers to utilize the soil water and nutrients in drought seasons [47]. On the other hand, the N availability for maize played a decisive role in maintaining the crop yield. The soil N supply was not a limiting factor due to high soil indigenous N, residual N from the previous seasons, as well as net N mineralization of organic N from organic matter in the rich rainfall years [48]. This could be the reason why the grain yield was not significantly different across treatments in 2019 with the wet growing season (Figure 1). These results might suggest that plow tillage with straw incorporation into soil has a great potential to increase or maintain the maize grain yield in the face of climate change in northeast China.

4.3. Modeling Analysis of the Impacts of Tillage and Straw Managements on Maize Grain Yield via Altering Soil Properties

The sustainable production of soil is mainly attributed to improving the soil nutrient levels and physical structure [15]. In this study, the SEM indicated that the soil physicochemical properties were mediated by the tillage depth and straw management, which could indirectly regulate the soil enzyme activities with consequences for crop production (Figure 7). Here, we indicated that the tillage depth tended to affect the soil PR and pH; however, straw management dominantly influenced the soil mineral N levels, leading to other soil property changes and crop production results, when comparing the tillage depth with the straw return factors. The soil NO$_3^–$–N content was the most important driver controlling the soil enzyme activities, which can be directly affected by straw management and indirectly influenced by tillage depth. In addition, soil enzymes mediated the soil nutrient availability for crop uptake and utilization [18], and directly played a part in the crop grain yield formation. These findings demonstrated that the straw return into the field, with any kind of tillage, could provide extra substrates and a favorable environment for inducing the production of soil enzymes, and further lead to changes in the soil nutrient dynamics supporting crop production sustainability [40,42].

5. Conclusions

Straw return, whether mixed or buried into the soil, had positive effects on increasing the supply of soil NO$_3^–$–N, promoting the SOC and STN contents in the surface soil layer (0–10 cm), and promoting the soil enzyme activity, ultimately resulting in a grain yield increase, especially in dry conditions. The management of the straw return into deep soil decreased the soil PR and enhanced the soil NO$_3^–$–N, SOC, and STN contents, further enriching the soil enzyme activities in the deep soil layer (30–40 cm). The treatment of straw buried into soil obtained higher grain yield in both years relative to the corresponding CK treatment. Taken together, our results indicate that straw incorporated by plow tillage into deeper soil depth in northeast China might be beneficial for strengthening the soil quality
protection and sustainable spring maize production, compared with traditional straw management with shallow tillage.

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**References**

1. Rattan, L. Restoring soil quality to mitigate soil degradation. *Sustainability* **2015**, *7*, 5875–5895.
2. Turmel, M.-S.; Speratti, A.; Baudron, F.; Verhulst, N.; Govaerts, B. Crop residue management and soil health: A systems analysis. *Agric. Syst.* **2015**, *134*, 6–16. [CrossRef]
3. Tian, P.; Sui, P.; Lian, H.; Wang, Z.; Meng, G.; Sun, Y.; Wang, Y.; Su, Y.; Ma, Z.; Qi, H.; et al. Maize straw returning approaches affected straw decomposition and soil carbon and nitrogen storage in Northeast China. *Agronomy* **2019**, *9*, 818. [CrossRef]
4. Tisdale, S.L.; Nelson, W.L.; Beaton, J.D. *Soil Fertility and Fertilizers*; Macmillan Publishing Company: New York, NY, USA, 1985.
5. Li, H.; Cao, Y.; Wang, X.; Ge, X.; Li, B.; Jin, C. Evaluation on the production of food crop straw in China from 2006 to 2014. *BioEnergy Res.* **2017**, *10*, 949–957. [CrossRef]
6. Qu, C.; Li, B.; Wu, H.; Giesy, J.P. Controlling air pollution from straw burning in China calls for efficient recycling. *Environ. Sci. Technol.* **2012**, *46*, 7934–7936. [CrossRef]
7. Zhang, J.; Hang, X.; Lamine, S.M.; Jiang, Y.; Afreh, D.; Qian, H.; Feng, X.; Zheng, C.; Deng, A.; Song, Z.; et al. Interactive effects of straw incorporation and tillage on crop yield and greenhouse gas emissions in double rice cropping system. *Agric. Ecosyst. Environ.* **2017**, *250*, 37–43. [CrossRef]
8. Zhang, S.; Li, Q.; Zhang, X.; Wei, K.; Chen, L.; Liang, W. Effects of conservation tillage on soil aggregation and aggregate binding agents in black soil of Northeast China. *Soil Tillage Res.* **2012**, *124*, 196–202. [CrossRef]
9. Mu, X.; Zhao, Y.; Liu, K.; Ji, B.; Guo, H.; Xue, Z.; Li, C. Responses of soil properties, root growth and crop yield to tillage and crop residue management in a wheat–maize cropping system on the North China Plain. *Eur. J. Agron.* **2016**, *78*, 32–43. [CrossRef]
10. Chen, Z.; Ji, J.; Chen, F. Soil aggregates response to tillage and residue management in a double paddy rice soil of the Southern China. *Nutr. Cycl. Agroecosyst.* **2017**, *109*, 103–114. [CrossRef]
11. Cerdà, A.; González–Pelayo, Ó.; Giménez–Morera, A.; Jordán, A.; Pereira, P.; Novara, A.; Brevik, E.C.; Prosdocimi, M.; Mahmoodabadi, M.; Keesstra, S.; et al. Use of barley straw residues to avoid high erosion and runoff rates on persimmon plantations in Eastern Spain under low frequency–high magnitude simulated rainfall events. *Soil Res.* **2016**, *54*, 154. [CrossRef]
12. Li, H.; Zhang, Y.; Yang, S.; Wang, Z.; Feng, X.; Liu, H.; Jiang, Y. Variations in soil bacterial taxonomic profiles and putative functions in response to straw incorporation combined with N fertilization during the maize growing season. *Agric. Ecosyst. Environ.* **2019**, *283*, 106578. [CrossRef]
13. Zhao, S.; Li, K.; Zhou, W.; Qiu, S.; Huang, S.; He, P. Changes in soil microbial community, enzyme activities and organic matter fractions under long–term straw return in north–central China. *Agric. Ecosyst. Environ.* **2016**, *216*, 82–88. [CrossRef]
14. Sommer, R.; Ryan, J.; Masri, S.; Singh, M.; Diekmann, J. Effect of shallow tillage, moldboard plowing, straw management and compost addition on soil organic matter and nitrogen in a dryland barley/wheat–vetch rotation. *Soil Tillage Res.* **2011**, *115*, 39–46. [CrossRef]
15. Dikgwatle, S.B.; Chen, Z.-D.; Lal, R.; Zhang, H.-L.; Chen, F. Changes in soil organic carbon and nitrogen as affected by tillage and residue management under wheat–maize cropping system in the North China Plain. *Soil Tillage Res.* **2014**, *144*, 110–118. [CrossRef]
16. Xue, J.-F.; Pu, C.; Liu, S.-L.; Chen, Z.-D.; Chen, F.; Xiao, X.-P.; Lal, R.; Zhang, H.-L. Effects of tillage systems on soil organic carbon and total nitrogen in a double paddy cropping system in Southern China. *Soil Tillage Res.* **2015**, *153*, 161–168. [CrossRef]
17. Pu, C.; Kan, Z.-R.; Liu, P.; Ma, S.-T.; Qi, J.-Y.; Zhao, X.; Zhang, H.-L. Residue management induced changes in soil organic carbon and total nitrogen under different tillage practices in the North China Plain. *J. Integr. Agric.* 2019, 18, 1337–1347. [CrossRef]

18. Heijboer, A.; Berge, H.E.T.; De Ruiter, P.C.; Jørgensen, H.B.; Kowalchuk, G.A.; Bloem, J. Plant biomass, soil microbial community structure and nitrogen cycling under different organic amendment regimes; a 15N tracer–based approach. *Appl. Soil Ecol.* 2016, 107, 251–260. [CrossRef]

19. Lu, F. How can straw incorporation management impact on soil carbon storage? A meta–analysis. *Mitig. Adapt. Strat. Glob. Chang.* 2014, 20, 1545–1568. [CrossRef]

20. Yang, H.; Feng, J.; Zhai, S.; Dai, Y.; Xu, M.; Wu, J.; Shen, M.; Bian, X.; Koide, R.T.; Liu, J. Long–term ditch–buried straw return alters soil water potential, temperature, and microbial communities in a rice–wheat rotation system. *Soil Tillage Res.* 2016, 163, 21–31. [CrossRef]

21. Sarker, J.R.; Singh, B.P.; Fang, Y.; Cowie, A.L.; Dougherty, W.J.; Collins, D.; Dalal, R.C.; Singh, B.K. Tillage history and crop residue input enhanced native carbon mineralization and nutrient supply in contrasting soils under long–term farming systems. *Soil Tillage Res.* 2019, 193, 71–84. [CrossRef]

22. Helgason, B.; Gregorich, E.; Janzen, H.H.; Ellert, B.H.; Lorenz, N.; Dick, R. Long–term microbial retention of residue C is site–specific and depends on residue placement. *Soil Biol. Biochem.* 2014, 68, 231–240. [CrossRef]

23. Schneider, F.; Don, A.; Hennings, I.; Schmittmann, O.; Seidel, S.J. The effect of deep tillage on crop yield–What do we really know? *Soil Tillage Res.* 2017, 174, 193–204. [CrossRef]

24. Essel, E.; Xie, J.; Deng, C.; Peng, Z.; Wang, J.; Shen, J.; Xie, J.; Coulter, J.A.; Li, L. Bacterial and fungal diversity in rhizosphere and bulk soil under different long–term tillage and cereal/legume rotation. *Soil Tillage Res.* 2019, 194, 104302. [CrossRef]

25. Nyborg, M.; Solberg, E.; Izaurralde, R.; Malhi, S.; Molina-Ayala, M. Influence of long–term tillage, straw and N fertilizer on barley yield, plant–N uptake and soil–N balance. *Soil Tillage Res.* 1995, 36, 165–174. [CrossRef]

26. Christian, D.; Bacon, E.; Brockie, D.; Glen, D.; Gutteridge, R.J.; Jenkyn, J. Interactions of straw disposal methods and direct drilling or cultivations on winter wheat (*Triticum aestivum*) grown on a clay soil. *J. Agric. Eng. Res.* 1999, 73, 297–309. [CrossRef]

27. Malhi, S.S.; Nyborg, M.; Solberg, E.; Dyck, M.; Puurveen, D. Improving crop yield and N uptake with long–term straw retention in two contrasting soil types. *Field Crop. Res.* 2011, 124, 378–391. [CrossRef]

28. Brennan, J.; Hackett, R.; McCabe, T.; Grant, J.; Fortune, R.; Forristal, P. The effect of tillage system and residue management on grain yield and nitrogen use efficiency in winter wheat in a cool Atlantic climate. *Eur. J. Agron.* 2014, 54, 61–69. [CrossRef]

29. You, D.; Tian, P.; Sui, P.; Zhang, W.; Yang, B.; Qi, H. Short–term effects of tillage and residue on spring maize yield through regulating root–shoot ratio in Northeast China. *Sci. Rep.* 2017, 7, 13314. [CrossRef]

30. Hu, N.; Wang, B.; Gu, Z.; Tao, B.; Zhang, Z.; Hu, S.; Zhu, L.; Meng, Y. Effects of different straw returning modes on greenhouse gas emissions and crop yields in a rice–wheat rotation system. *Agric. Ecosyst. Environ.* 2016, 223, 115–122. [CrossRef]

31. Liu, Z.; Yang, X.; Hubbard, K.G.; Lin, X. Maize potential yields and yield gaps in the changing climate of northeast China. *Glob. Chang. Biol.* 2012, 18, 3441–3454. [CrossRef]

32. Joseph, G.; Henry, H.A. Soil nitrogen leaching losses in response to freeze–thaw cycles and pulsed warming in a temperate old field. *Soil Biol. Biochem.* 2008, 40, 1947–1953. [CrossRef]

33. Wang, Q.-Y.; Zhou, D.-M.; Cang, L. Microbial and enzyme properties of apple orchard soil as affected by long–term application of copper fungicide. *Soil Biol. Biochem.* 2009, 41, 1504–1509. [CrossRef]

34. Peng, X.; Wang, W. Stoichiometry of soil extracellular enzyme activity along a climatic transect in temperate grasslands of northern China. *Soil Biol. Biochem.* 2016, 98, 74–84. [CrossRef]

35. Karlen, D.L.; Mausbach, M.J.; Doran, J.W.; Cline, R.G.; Harris, R.F.; Schuman, G.E. Soil quality: A concept, definition, and framework for evaluation. *Soil Sci. Soc. Am. J.* 1997, 61, 4–10. [CrossRef]

36. Chen, J.; Zheng, M.-J.; Pang, D.-W.; Yin, Y.-P.; Han, M.-M.; Li, Y.-X.; Luo, Y.-L.; Xu, X.; Li, Y.; Wang, Z.-L. Straw return and appropriate tillage method improve grain yield and nitrogen efficiency of winter wheat. *J. Integr. Agric.* 2017, 16, 1708–1719. [CrossRef]

37. Zhou, Y.; Zhang, Y.; Tian, D.; Mu, Y. The influence of straw returning on N2O emissions from a maize–wheat field in the North China Plain. *Sci. Total Environ.* 2017, 584, 935–941. [CrossRef]

38. Francis, G. Management practices for minimising nitrate leaching after ploughing temporary leguminous pastures in Canterbury, New Zealand. *J. Contam. Hydrol.* 1995, 20, 313–327. [CrossRef]
39. Sui, P.X.; Tian, P.; Lian, H.L.; Wang, Z.Y.; Ma, Z.Q.; Qi, H.; Mei, N.; Sun, Y.; Wang, Y.Y.; Su, Y.H.; et al. Tillage incorporation management affects maize grain yield through regulating root distribution and nitrogen uptake. *Agronomy* 2020, 10, 324. [CrossRef]

40. Heinze, S.; Rauber, R.; Joergensen, R.G. Influence of mouldboard plough and rotary harrow tillage on microbial biomass and nutrient stocks in two long-term experiments on loess derived Luvisols. *Appl. Soil Ecol.* 2010, 46, 405–412. [CrossRef]

41. Urioste, A.; Hevia, G.; Hepper, E.; Anton, L.; Bono, A.; Buschiazzo, D. Cultivation effects on the distribution of organic carbon, total nitrogen and phosphorus in soils of the semiarid region of Argentinian Pampas. *Geoderma* 2006, 136, 621–630. [CrossRef]

42. Kabiri, V.; Raiesi, F.; Ghazavi, M.A. Tillage effects on soil microbial biomass, SOM mineralization and enzyme activity in a semi-arid Calcixerepts. *Agric. Ecosyst. Environ.* 2016, 232, 73–84. [CrossRef]

43. López-Garrido, R.; Madejón, E.; León-Camacho, M.; Girón, I.; Moreno, F.; Murillo, J. Reduced tillage as an alternative to no-tillage under Mediterranean conditions: A case study. *Soil Tillage Res.* 2014, 140, 40–47. [CrossRef]

44. Dick, R.P.; Rasmussen, P.E.; Kerle, E.A. Influence of long-term residue management on soil enzyme activities in relation to soil chemical properties of a wheat-fallow system. *Biol. Fertil. Soils* 1988, 6, 159–164. [CrossRef]

45. Xu, J.; Han, H.; Ning, T.; Li, Z.; Lal, R. Long-term effects of tillage and straw management on soil organic carbon, crop yield, and yield stability in a wheat-maize system. *Field Crop. Res.* 2019, 233, 33–40. [CrossRef]

46. Berhe, F.; Fanta, A.; Alamirew, T.; Melesse, A.M. The effect of tillage practices on grain yield and water use efficiency. *Catena* 2013, 100, 128–138. [CrossRef]

47. Guan, D.; Al-Kaisi, M.M.; Zhang, Y.; Duan, L.; Tan, W.; Zhang, M.; Li, Z. Tillage practices affect biomass and grain yield through regulating root growth, root-bleeding sap and nutrients uptake in summer maize. *Field Crop. Res.* 2014, 157, 89–97. [CrossRef]

48. Xu, X.; He, P.; Pampolino, M.F.; Li, Y.; Liu, S.; Xie, J.; Hou, Y.; Zhou, W. Narrowing yield gaps and increasing nutrient use efficiencies using the Nutrient Expert system for maize in Northeast China. *Field Crop. Res.* 2016, 194, 75–82. [CrossRef]

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