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Influence of Tillage on the Mollisols Physicochemical Properties, Seed Emergence and Yield of Maize in Northeast China

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Abstract: Tillage practices are critical for sustaining soil quality necessary for successful crop growth and productivity, but there are only few studies for strip tillage (ST) in the Mollisols region of Northeast China at present. A long-term (≥10-year) study was carried out to investigate the influence of within the tilled row (IR) and between rows (BR) in ST (10-year), conventional tillage (CT, 14-year) and no tillage (NT, 14-year) treatments on soil physicochemical properties. Soil samples were taken in May of 2019 at 0–5, 5–10, 10–20 and 20–30 cm depths and used to analyze bulk density (BD), soil aggregate distribution and stability, and soil organic carbon (SOC). Meanwhile, our study also explored the differences in seed emergence, soil moisture, and temperature during the seed emergence period, and yield of maize (*Zea mays* L.) among the different treatments. Similar soil properties were observed between ST-BR and NT, which showed they had a significantly greater BD, >0.25 mm water stable aggregate content ($WR_{0.25}$) (especially in the amount of >2 mm and 1–2 mm size proportion), aggregate stability, and SOC than ST-IR and CT-IR at a depth of 0–20 cm. By improving soil conditions of seedbed, ST-IR and CT-IR increased soil temperature above NT by 1.64 °C and 1.80 °C, respectively, and ST-IR had a slight greater soil moisture than CT-IR in the top 10 cm layer during the seed emergence period. Late maize seed emergence was observed NT in than ST-IR and CT-IR and the average annual yields in ST were slightly greater than NT and CT, but the differences were not significant. Our results also showed that CT-BR had a poor soil structure and lower SOC than other treatments at 0–30 cm depth. We conclude from these long-term experimental results that ST could improve soil water-heat conditions to promote seed germination, maintain soil structure, and increase the maize yield and it should be applied in the Mollisols region of Northeast China.

Keywords: tillage; Mollisols; soil structure; soil organic carbon; soil moisture; soil temperature; seed emergence; yield

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1. Introduction

Soil tillage focuses on improving crop yields and at the same time preserving ecological soil functions. However, in recent decades, conventional tillage (CT) has been recognized as a major driver of soil erosion and nutrient loss from cultivated land [1]. In response to these problems, conservation tillage systems such as no tillage (NT) and strip tillage (ST) are used as the generic technology to preserve regulatory functions for soil water and nutrients [2,3].

Mollisols were classified as Phaeozems by US Soil Taxonomy (USST) and as Black soil by Chinese Soil Taxonomy (CST) [4]. The Mollisols region of Northeast China is one of the most important bases for commercial grain production in China, thereby playing a crucial role in China's food security [5]. CT is the dominant tillage practice in this region; however, these intensive cultivation and residue removal practices have caused the severe soil degradation of soil structure, and the on-going soil degradation has threatened sustainable crop production and even national food security [6]. NT is an important conservation tillage practice, which can be effective in controlling soil erosion, improving soil quality, and reducing input costs and labor needs in this region [3,7]. However, some researchers observed that NT can result in lower crop yields because NT soils with crop residues tend to stay wetter and cooler longer in spring [8,9], which could potentially lead to delay seed germination, impeded root growth, and crop nutrient uptake, and result in reduced yields compared to CT [10–12]. Hence, it is hard for local farmers to accept NT as a priority or major pattern of cultivation in farmland.

ST is relatively new, having been first evaluated in the early 1990s. It is a form of conservation tillage in which disturbance of less than one third of the total fields is limited to the crop rows, while the rest of the soil remains undisturbed, which incorporates the benefits of soil and water conservation of NT and the improved seedbed conditions of CT [13,14]. ST offers a unique opportunity to apply nutrients, and a crop is seeded or planted into a narrow-tilled row that is 20 to 40 cm depending on equipment and crop, which improves soil temperature and moisture conditions and promotes germination and emergence of crop seeds compared to NT [13,15–17]. Soils between rows are left undisturbed and straw mulching management is used, which might prevent soil from erosion and maintain soil quality, reduce both tillage costs and the pollution from directly burning of straw—advantages that ST provides compared with CT [18].

To respond to these problems of NT and CT, ST might be adopted in this region. However, no studies have compared long-term NT, ST, and CT on soil properties within the tilled row (IR) and between rows (BR) in the Mollisols region of Northeast China. Meanwhile, the effect of ST on seed emergence and yield remains unclear in this region. For these reasons, the objectives of this study are: (1) to investigate the effect of ST-IR and ST-BR on soil physicochemical properties when compared with CT and NT; (2) to analyze the maize seed emergence and yield in different tillage treatments. These results could provide a basis for enriching the theoretical research on conservation tillage and agricultural sustainable utilization in Northeast China.

2. Materials and Methods

2.1. Experimental Site

The field experiment is located at the Hailun Monitoring and Research Station of Mollisols Erosion, Chinese Academy of Sciences (47°21′ N, 126°50′ E), located in the north temperature zone with continental monsoon conditions (cold and arid in winter, hot and rainy in summer). Annual average temperature is 1.5 °C and average annual precipitation is 530 mm with an average precipitation of 528.2 mm from March to October in 2006–2019. The soils are classified as Mollisols (USST) with silty clay loam texture and a rich organic depth [4,19]. The physical and chemical properties of soil are shown in Table 1.

Table 1. Physical and chemical properties of test soil.

Soil Depth (cm)	Organic Matter ($g \cdot kg^{-1}$)	Bulk Density ($g \cdot cm^{-3}$)	Field Capacity (%)	Saturated Content (%)	Wilting Point (%)	Clay Content (%)
0–20	49.1	1.25	38.5	50.5	17.2	40.8
20–30	44.8	1.29	36.9	45.4	17.1	39.9

2.2. Experimental Design

The experiment was a randomized complete-block design with three replications, and the main plot included three tillage treatments: strip tillage (ST), no tillage (NT), and conventional tillage (CT). The NT and CT experimental plots were built in 2006 and the ST experimental plot was established in 2010. Individual treatment plots were 40 m × 8.4 m with soybean and maize rotation. The fields had a mean slope of 5% in east-west direction.

In 2019, for ST, the strips that were 0.10 m depth and 0.25 m wide, were prepared only one time in previous fall, and maize was planted with a strip-tillage seeder on 7 May without any further tillage, and crop residue was removed from the cultivated strips and placed between rows. For NT, only the crop seed was harvested, and all crop residue except harvested seeds was evenly distributed across the plot to cover the surface. Maize was planted into a narrow-tilled row with a no-till planter on 7 May. There were no other soil tillage practices and surface biomass was approximate 4 t for soybean and 10 t for maize used in ST and NT. For CT, all above-ground biomass was removed manually and ridged by rotary tillage in the autumn. Maize was planted on the top of ridges in these plots with a conventional planter on 7 May. The field was ridged twice at time intervals of 15 days after planting. Field management was the same for all treatments except tillage operations. Fertilizer was applied at 20.25 kg $N{\cdot}ha^{-1}$, 51.75 kg $P{\cdot}ha^{-1}$, and 15 kg $K{\cdot}ha^{-1}$ for soybean, and 138 kg $N{\cdot}ha^{-1}$, 51.75 kg $P{\cdot}ha^{-1}$, and 15 kg $K{\cdot}ha^{-1}$ for maize. Weeds were controlled by herbicides of Acetochlor (1500 $mL{\cdot}ha^{-1}$) and Thifensulfuron-methyl (120 $g{\cdot}ha^{-1}$) one day after planting. The plant populations were 5.3 $plants{\cdot}m^{-2}$ for maize.

2.3. Soil Sampling

Soil sampling for ST and CT was conducted both within the tilled row (IR) and in the non-tilled area between rows (BR). In all three tillage treatments (ST, NT, and CT), sampling time was in the seed emergence period. Soil samples were collected by self-made sampling shovel at the 0–5 cm, 5–10 cm, 10–20 cm, and 20–30 cm depth, and each soil sample was comprised of a mixture of upper, middle, and lower positions of each plot. Three random samples of each soil layer in the same plots were mixed together and placed in the polyethylene bags. All samples were air dried and passed through a 10 mm sieve for soil water stable aggregate determination, and the samples of the stones and crop residues were removed and ground to pass a 0.25-mm sieve for SOC analysis.

2.4. Data Collection and Soil Analyses

The average daily soil temperature and moisture for ST-IR, CT-IR, and NT were measured by SMEC 300 device (WaterScout, Graton, CA, USA) at a depth of 10 cm in the seed emergence period. Support for weather data collection at the experimental site was provided by the Hailun Monitoring and Research Station of Mollisols Erosion, CAS.

BD for each plot was measured by using a steel cylinder measuring 5 cm in diameter and 5 cm high, and repeated three times, at four different layers: 0–5 cm, 5–10 cm, 13–18 cm, and 23–28 cm. Soil samples were dried at 105 °C for at least 48 h and then weighed. BD results from the 13–18 cm and 23–28 cm cylinders were used to represent, respectively, the 10–20 cm and 20–30 cm layers.

As aggregate stability is measured on various aggregate sizes depending on the high-vacuum slow wetting method [20], five aggregate size classes (2 mm, 1 mm, 0.5 mm, 0.25 mm, and 0.053 mm) have been used in order to test the influence of initial aggregate size on the size distribution of breakdown fragments. The mass of each of six aggregate fractions (<0.053 mm, 0.053–0.25 mm, 0.25–0.5 mm, 0.5–1 mm, 1–2 mm and >2 mm) was recorded as $W_{wi,}$ and the relative percentage was calculated as:

W_i was the proportion of the weight of the size aggregates fraction, and the formula is as follows:

$$W_i = \frac{W_{wi}}{50} \times 100\%$$

The amount of >0.25 mm size water stable aggregates ($WR_{0.25}$) and mean weight diameter (MWD) were calculated as:

$$WR_{0.25} = 1 - \frac{M_{r>0.25}}{MT}$$

$$MWD = \frac{\sum_{i=1}^{n} (\overline{X}i \cdot Wi)}{\sum_{i=1}^{n} Wi}$$

The fractal dimension (D_m) was estimated from the following equation [21]:

$$\frac{M(r < \overline{X}i)}{M_T} = \left(\frac{\overline{X}i}{X_{max}}\right)^{3-D}$$

where X_i is the mean particle diameter (mm) of the ith size class, M_r is the cumulative mass of particles of *i*th size r less than X_i, M_T is the total mass, and X_{max} is the mean diameter of the largest particle, respectively. The mean particle diameter was taken as the arithmetic mean of the upper and lower sieve sizes.

SOC was determined by VarioEL III element analyzer (Elementar, Langenselbold, Germany).

Mean emergence time (MET), emergence rate index (ERI), and percentage of emergence (PE) of maize were determined using the following equations [22,23]:

$$MET = \frac{N1 * T1 + N2 * T2 + \ldots + N\mathrm{n} * Tn}{N1 + N2 + \ldots N\mathrm{n}}$$

$$ERI = \frac{Ste}{MET}$$

$$PE = \frac{100\% S\mathrm{te}}{n}$$

where MET is the mean emergence time (day), ERI is the emergence rate index (seeding day·m^{-1}), PE is the percentage of emergence (%), N1 ... n is the number of seedlings emerging since the time of previous count; T1 ... n is the number of days after sowing; Ste is the number of total emerged seedlings per meter, n is the number of seeds sown per meter.

Maize yield was determined by manually harvesting each plot annually, and crop yield was reported after being converted to 14% water content.

2.5. Statistical Analysis

The SPSS analytical software 22.0 was used for all of the statistical analyses. All data was analyzed using a one-way ANOVA and means comparison using the Tukey test. A protected LSD (0.05) value was used to establish if the differences in the treatments were significant. Figures were generated using Sigmaplot 12.0 (Systat Software Inc., San Jose, CA, USA).

3. Results

3.1. Bulk Density

CT-BR had a greater BD compared with other treatments at a depth of 0–30 cm (Figure 1) and no significant differences in BD were observed in between ST-IR and CT-IR, between ST-BR and NT, respectively. BD in ST-BR was slightly higher than in NT, which varied from 1.16 g·cm^{-3} to 1.24 g·cm^{-3} at a depth of 0–30 cm. In the top soil of 0–10 cm, the BD values in ST-IR and CT-IR had a significantly lower value than ST-BR and NT, and the differences in BD among these treatments decreased with the increase in soil depth.

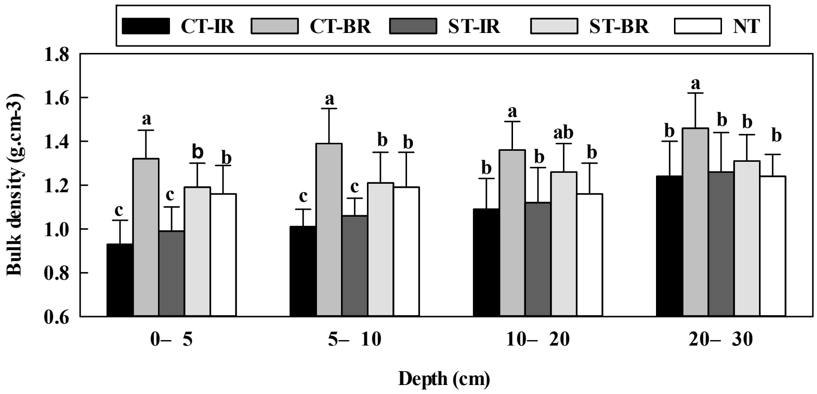

Figure 1. Differences in bulk density among the different tillage treatments. Notes: Values followed by the different lowercase letters in the same depth had significant differences at 0.05 level. ST: Strip tillage; NT: no tillage; CT: conventional tillage; IR: within the tilled planting row; BR: between the planting rows.

3.2. Soil Aggregate Distribution

At a depth of 0–5 cm, the greatest proportion of soil in both ST-BR and NT was observed in the 0.5–1 mm size fraction and the main proportion of soil in ST, NT, and CT-IR was in the 0.25–0.5 mm size fraction at the depth of 5–20 cm (Figure 2). The greatest <0.053 mm size fraction was observed in CT-BR at a depth of 0–30 cm and in other treatments at a depth of 20–30 cm.

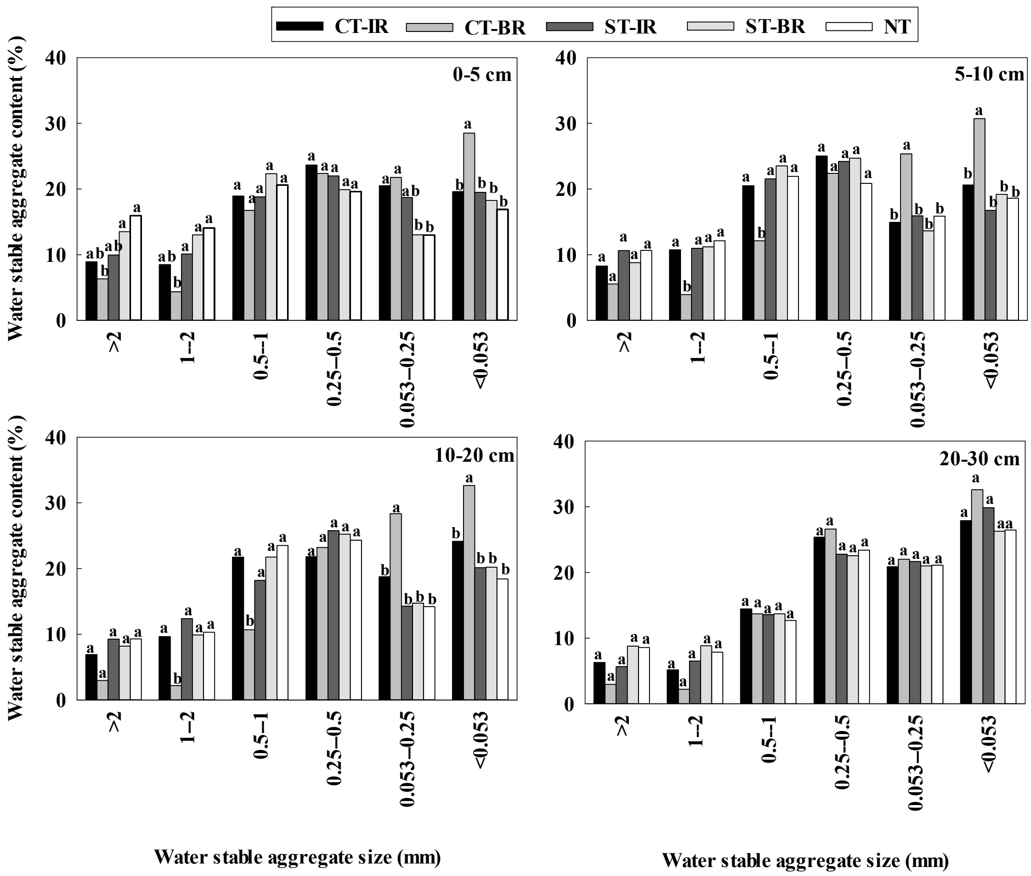

Figure 2. Differences of water stable aggregate size distribution in different tillage treatments. Notes: Values followed by the different lowercase letters in the same aggregate size had significant differences at 0.05 level.

At a depth of 0–30 cm, there were no significant differences in the proportion of soil in the 0.25–0.5 mm classes among all the tillage treatments. The average amount of soil in the >2 mm and 1–2 mm size fractions in both ST-BR and NT at the depth of 0–5 cm was 8.20%, 8.63%, and 9.60%, 9.70% higher than that in CT-BR, respectively, while the proportion of soil in the <0.25 mm size fraction in CT-BR was significantly greater than that in other treatments. The study also found that the amount of soil in the 1–2 mm and 0.5–1 mm size fractions in CT-BR were significantly lower than that in other treatments, but there was no significant difference among all the tillage treatments at a depth of 20–30 cm. No significant differences in different aggregate size fractions were observed between ST-IR and ST-BR.

3.3. Aggregate Stability

Aggregate stability varied greatly among all the tillage treatments (Table 2). No significant differences in the amount of >0.25 mm size proportion ($WR_{0.25}$) at a depth of 0–30 cm were observed between ST-BR and NT, and between ST-IR and CT-IR, respectively. It was also found that NT had a greatest $WR_{0.25}$ compared to other treatments, while the lowest $WR_{0.25}$ was observed in CT-BR.

Table 2. Differences in $WR_{0.25}$, MWD and the fractal dimension (D_m) under different tillage system treatments.

Depth (cm)	Tillage	$WR_{0.25}$ (%)	MWD (mm)	D_m	Depth (cm)	Tillage	$WR_{0.25}$ (%)	MWD (mm)	D_m
0–5	CT-IR	59.90 b	0.92 c	2.34 b	5–10	CT-IR	64.47 a	0.93 b	2.25 b
	CT-BR	49.76 c	0.68 d	2.53 a		CT-BR	43.95 b	0.61 c	2.58 a
	ST-IR	60.82 b	1.01 c	2.20 c		ST-IR	65.34 a	0.92 b	2.19 b
	ST-BR	68.73 ab	1.27 b	2.16 c		ST-BR	68.18 a	1.08 a	2.17 b
	NT	72.15 a	1.42 a	2.11 c		NT	68.55 a	1.10 a	2.20 b
10–20	CT-IR	60.10 a	0.94 a	2.34 b	20–30	CT-IR	57.27 a	0.70 a	2.48 a
	CT-BR	39.04 b	0.43 b	2.64 a		CT-BR	40.45 b	0.45 b	2.56 a
	ST-IR	65.60 a	1.00 a	2.23 c		ST-IR	52.49 a	0.69 a	2.52 a
	ST-BR	65.08 a	0.93 a	2.24 c		ST-BR	57.78 a	0.78 a	2.49 a
	NT	67.38 a	1.01 a	2.19 c		NT	59.46 a	0.75 a	2.46 a

Notes: Values followed by the different lowercase letters in the same depth had significant differences at 0.05 level.

At the depth of 0–30 cm, there was significantly lower MWD for CT-BR than other tillage treatments, which showed the aggregates to be very unstable. The MWD in ST-BR at the depth of 0–5 cm was significantly lower than in NT, but no significant differences were observed between ST-BR and NT at a depth of 5–30 cm. The MWD values in ST (ST-IR and ST-BR) and NT were greater than that in CT (CT-IR and CT-BR). Similar to the results of MWD, the fractal dimension (D_m) in NT and ST was significantly lower than in CT at a depth of 0–5 cm and 10–20 cm. However, there was no significant difference in D_m among all the tillage treatments at the depth of 20–30 cm. Our study also observed that the differences in aggregate stability among all the tillage treatments decreased with the increase of soil depth.

3.4. Soil Organic Carbon

At a depth of 0–5 cm, tillage treatments substantially affected SOC in the order: NT > ST-BR > ST-IR > CT-IR > CT-BR (Table 3). Among them, the SOC values in NT and ST-BR were 5.11 g·kg^{-1} and 7.28 g·kg^{-1}, 3.72 g·kg^{-1} and5.89 g·kg^{-1} higher than that of CT-IR and CT-BR, respectively. ST-IR was significantly higher in SOC than CT. Below the depth of 5 cm soil, little differences of SOC were observed among all the treatments, but CT had a slightly lower than ST and NT as a whole. The SOC values in all the tillage treatments showed a decline trend with the increase of soil depth.

Table 3. Differences of soil organic carbon in the different tillage treatments.

Depth (cm)	Soil Organic Carbon (g·kg^{-1})				
	ST-IR	**ST-BR**	**NT**	**CT-IR**	**CT-BR**
0–5	26.82 b	28.81 a	30.20 a	25.09 c	22.92 d
5–10	26.09 a	26.22 a	26.73 a	25.71 a	23.87 b
10–20	22.83 a	22.15 a	22.99 a	21.03 a	20.46 a
20–30	18.35 a	18.61 a	19.05 a	19.47 a	18.00 a

Notes: Values followed by the different lowercase letters in the same depth had significant differences at 0.05 level.

3.5. Soil Moisture and Soil Temperature

The average soil moisture at a depth of 0–10 cm in ST-IR was 2.77% lower than in NT and 1.21% higher than in CT-IR during the seed emergence period (Figure 3a). Greater temporal variation was observed in ST-IR and CT-IR compared to NT. The results showed that soil moisture in both ST-IR and CT-IR decreased by 6.37% and 5.72% respectively, from 6 to 11 May, while that of NT decreased by 3.51%. The average soil temperature at a depth of 10 cm in ST-IR and CT-IR was 1.64 °C and 1.80 °C greater than in NT, respectively (Figure 3b). This study also observed similar variation of soil temperature in ST-IR and CT-IR, and their changes, which fluctuated with air temperature, were greater than NT. From 22 to 24 May, the average daily air temperature increased from 9.63 °C to 22.98 °C and the average daily soil temperature in ST-IR, CT-IR and NT increased by 6.99 °C, 6.80 °C and 2.24 °C, respectively. While from 25 to 26 May, the mean daily air temperature decreased rapidly from 21.52 °C to 11.17 °C, and the mean daily soil temperature in ST-IR, CT-IR and NT decreased by 6.98 °C, 7.13 °C and 2.19 °C, respectively. However, the mean daily soil temperature in both ST-IR and CT-IR were 1.39 °C and 1.94 °C, respectively.

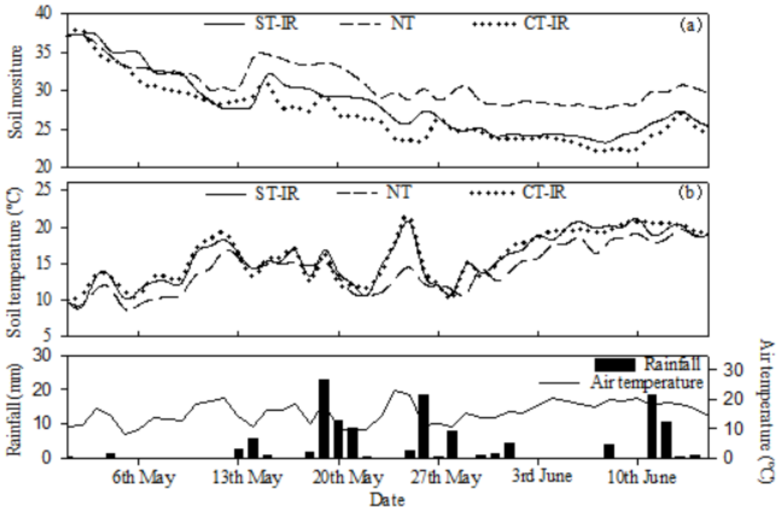

Figure 3. Dynamic changes of soil moisture (**a**) and soil temperature (**b**) under different tillage treatments at the depth of 0–10 cm in 2019.

3.6. Seed Emergence and Yield of Maize

The mean emergence time (MET) in ST was 3.9 days earlier and the percentage of emergence (PE) was 8.34% greater than in NT (Table 4). Meanwhile, ST had a greater the emergence rate index (ERI) than NT. Similar results were observed in CT, which showed that MET, ERI, and PE were significantly greater than those in NT. No significant differences in seed emergence were observed between ST and CT.

Table 4. Differences of the seeding emergence values and yield of maize in different tillage treatments.

Tillage	MET [a] (Day)	ERI [b] (Seedlings/d·m)	PE [c] (%)	Yield (kg·ha^{-1})						
				2009	2011	2013	2015	2017	2019	Mean
ST	21.3 b	0.224 a	90.10 a		8225 abB	8775 bAB	9477 aA	9133 aA	9239 aA	8970 a
NT	25.2 a	0.172 b	81.76 b	6822 bD	8030 bC	9527 aAB	9850 aA	9129 aAB	8975 aB	8722 a
CT	20.9 b	0.245 a	96.46 a	8096 aC	8835 aB	8570 bBC	9740 aA	8612 aBC	9146 aAB	8883 a

Notes: Values followed by the different capital letters in the same tillage had significant differences at 0.05 level; Values followed by the different lowercase letters in the same treatment had significant differences at 0.05 level. [a] MET, mean emergence time; [b] ERI, emergence rate index; [c] PE, Percentage of emergency.

Maize yield was significantly different among three tillage treatments. The yield differences between all three tillage treatments decreased over time and with no differences occurred after 2015, which showed that ST had a slight greater average yield than NT and CT (Table 4). An increase in maize yield was found at the beginning of the ST treatment compared to NT (6-year), and a little greater occurred in ST than NT and CT in 2017 and 2019. Maize yields in NT were lower than those for CT during the study years of 2009 and 2011, with observed yield reduction from 1.91% to 18.67%. Significantly greater yields occurred in 2013 for NT than ST and CT. With the increasing length of time since establishment of tillage treatments, our study also suggested that the mean maize yield (2013–2019) in ST, NT and CT treatments significantly increased 11.26%, 37.35% and 10.21%, respectively.

4. Discussion

4.1. Effects of Tillage on Soil Properties

Strip tillage (ST), a soil conservation-oriented primary tillage, creates two distinct soil structures which are beneficial in terms of optimal plant growth as well as mechanical resistance by driving over the soil. It combines the advantages of NT and CT by creating a narrow tilled planting row (IR) that provides a good seedbed condition while leaving the non-tilled area between the planting row (BR) covered with crop residue. Our study showed that similar soil properties were observed between ST-IR and CT-IR, and between ST-BR and NT, respectively.

Chen et al. [9] observed that NT led to significant BD increment and a significantly lower soil macroporosity than CT at 0–20 cm, while Jabro et al. [24] found that ST-IR reduced soil compaction, consequently leading to increased total porosity and lower BD than NT. Similar results were found in our study; significant greater BD in CT-BR, ST-BR, and NT were observed compared to that in ST-IR and CT-IR at a depth of 0–10 cm during the seed emergence period. Due to no straw mulching, CT-BR might lead to the formation of surface runoff and soil erosion in the rainy season. Similar results were reported by other studies [25–27].

The higher the stability of aggregates, the more conducive conditions become to the growth and development of crops, but also for resistance to soil erosion. Our study clearly observed that there were significant differences on soil aggregate distribution and stability among all the tillage treatments. At a depth of 0–5 cm, the proportion of soil in $WR_{0.25}$ fraction under CT-BR was significantly lower than other treatments, especially in the >2 mm and 1–2 mm size fraction. Numerous studies had also proved that CT-BR had a poor soil aggregate structure due to mechanical compaction and excessive disturbance of soil, which led to increasing occurrence of soil erosion in the rainy season [27,28]. Meanwhile, greater aggregate stability was observed in ST and NT compared with CT and no differences or inconsistent responses to tillage for aggregate stability with NT and ST, which showed the aggregates to be very stable. Similar results were reported by [29]. These were attributed to the application of straw mulching and little soil disturbance for ST-BR and NT, which effectively reduced raindrop splash erosion, and then to a decline in aggregate crushing, and crop residue was degraded to provide a great amount of organic matters and to promote the formation of large size aggregates [30–34]. Stable soil aggregates reduce the negative effects of tillage on other soil physical properties, and erosion by wind and water [33]. These results suggested that land management might be an important consideration when evaluating soil physical parameters. Our study also found that soil physical parameter differences among the treatments decreased as the depth increased, which indicates that different tillage treatments mainly affect the proportion of soil in aggregates in the tillage layer (0–20 cm depth).

The impact of tillage and straw mulching on SOC sequestration (net increase) or loss has been the focus on many studies, and the different years since the establishment of tillage treatments might be an important consideration when evaluating SOC. Conservation tillage treatments (NT or ST) generally could increase the sequestration of soil C in the topsoil (0–5 cm) compared with CT, but this increase might take approximately 5–10 years to be obvious [35–38]. Similar results were reported by our study, which suggested that NT (14-year) and ST (10-year) had a greater SOC than CT (14-year). The higher SOC content in ST and NT might be due to slower decomposition of residues. The SOC values showed similar results to aggregate stability, with an accumulation in the top layer (0–5 cm), and a clear decrease with depth, for all the tillage treatments. In addition, ST could increase soil microbial activity and soil mineralized nitrogen and activated carbon [5,39]. In short-term period, effects of conservation tillage on soil C dynamics are uncertain [40–42].

Our previous research found that CT-IR only had better soil structure during the seed emergence period, while NT had a beneficial effect on soil aggregate stability and infiltration capacity and improved SOC and soil nutrient throughout the growing season [43]. In addition, ST and NT have the potential to weaken the impact of wind and water erosion on soil ecological environment, to maintain or improve soil quality [44], and at the same time, disturbance soil area for ST is only about 30%, and ST has been shown to reduce tillage costs and machinery operating time by an average of $36.50 and 0.47 $h \cdot ha^{-1}$, respectively, as compared with CT [45].

4.2. Effects of Tillage on PE and Yield

Lower soil temperature and higher soil moisture, caused by surface straw mulching [8], may also contribute to reduced yields in cover crop–based NT compared with CT [13,14]. Compared with NT, ST offers a better seedbed for the crop IR and promotes soil warming and drying in the spring, which is important in geographic locations with cool, wet springs like the black soil region of Northeast China. Our study confirmed that the average soil temperature in ST-IR was 1.64 °C greater than NT during the seed emergence period, which might lead to higher PE and less MET for ST treatment. Similar results were reported by [14]. The different strip widths affect the seed emergence, Celik et al. [46] observed that soil temperature increased as strip width increased but soil moisture content decreased due to evaporation loss from the tilled surface of the strips. A 25 cm strip width was used to our study and little differences on PE and MET were observed between ST and CT. Meanwhile, ST-IR had a slightly higher soil moisture compared to CT-IR. Pöhlitz et al. [26] observed that ST-BR displayed an increasing saturated conductivity and increased soil moisture compared with CT, in part because straw mulching on the surface ground in ST can decrease evaporation [47].

NT tended to have greater yields than CT in hot and wet areas, while similar yields occurred in the warm and humid areas and lower NT yields were observed in the cool and semi-arid regions [48]. Our previous study has demonstrated that the average increase of soybean yield in NT (6-yr) was 8.9% and in contrast, a 28.4% decrease on the average maize yield in a flat farmland plot, near our sloping farmland plots, which also found that the greatest soybean yield response occurred in 2008 and 2010 when average yield in NT was 13.8% greater than that for CT [8]. This suggests that a significant increase of soybean yield and decrease of corn yield under NT compared to CT in the short-term (within 5-yr) was clearly shown in the cool humid region of Northeast China. In this study, our results observed that CT had greater maize yield than NT during all the three study years, and an approximate 20% decrease in maize yield was found in NT (3-yr) compared to CT (3-yr) in

2009. This might be an important reason to limit the popularization and application of NT. Reasons for lower yield potential in NT might be due to poor seedbed conditions, slower crop growth, and impeded root growth under non-inversion tillage practices [49]. These yield differences gradually change with time, and after 5 to 7 y, NT could improve soil structure and increase crop yields [50]. Our study demonstrated that the maize yield in NT treatments significantly increased from 2009 to 2019, and significantly greatly greater yields occurred in NT than in CT in 2013.

The initial ST treatment, introduced in 2011, tended to show increase in maize yield compared to NT that had been established 6 years prior to our study. Similar results were observed by other researchers [51,52]. ST might improve crop yields through changes in soil N dynamics; Fernández et al. [29] observed that ST significantly improved nutrient absorption efficiency compared with NT. This is mainly attributed to the loose seedbed environment and lower BD at a depth of 0–10 cm, which would indicate improved soil conditions for root penetration in ST compared to NT [29,49]. These are beneficial for the application of fertilizer directly to the roots in the process of fertilization, and to improve the fertilizer use efficiency during crop growth period [26,49]. Our results showed that CT had a significant greater yield than at the beginning of ST (in 2011) and NT (in 2009), which might be due to changes in soil characteristics, surface roughness, retention of straw mulching, nitrogen availability, fertilizer application, and weed control management, all of which may be observed in the early period of conversion from CT to conservation tillage (NT or ST) [3,53]. In addition, despite this initial yield reduction, the similar or higher yield subsequently observed with conservation tillage resulted in equivalent yields in the long term. Our results confirmed that small yield differences were observed among long-term CT (14-year), NT (14-year), and ST (10-year) treatments after 2015, and ST had a slightly higher average annual yield of maize than NT and CT. In addition, the 17-year average soybean yield in NT increased by 13% than CT in the same region (unpublished data). Similarly, Mullins et al. [54] determined that ST increased maize and grain yield by 14 and 30%, respectively, when compared to CT. Cruse [55] found that slight maize production increases with CT were not sufficient to offset differences in total production costs, which were lower with ST. Based on these results, the adoption of ST can be an effective strategy in promoting maize yields.

In this study, lower MET and PE were observed in NT than both ST and CT, but significant differences in maize yield were among all the treatments in 2019. These might be caused by field management practices, in which maize is reseeded in each tillage experimental plot for no seed germination area before the rainy season every year, and our yields data in this study do not take into account PE and MET factors. When these factors or no-reseed practices are considered, the maize yield in NT might be significantly lower than other treatments, and these management practices for large tracts of farmland have a lot of input costs and labor needs. As a consequence, it is hard for farmers to accept NT as a priority or major form of tillage in Northeast China.

5. Conclusions

ST creates two distinct soil structures which contrinbute to optimal plant growth and reduce soil erosion. Compared to NT, ST-IR creates a better seedbed environment, resulting in improved soil moisture and temperature conditions, reduces soil compaction, and promotes seedling emergence and nutrient uptake during the seed emergence period, which are beneficial to crop growth and increases the SOC content and yield. Meanwhile, compared to CT, ST-BR by straw mulching improves soil aggregate stability and increased SOC. In particular, it can effectively reduce soil loss and promote soil nutrients immobilization. Based on these results, it seems that ST combines the advantages of NT and CT, and is suitable for promotion and application in the black soil region of Northeast China.

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