



Soil Compaction and Maize Root Distribution under Subsoiling Tillage in a Wheat–Maize Double Cropping System

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Abstract: Huang-Huai-Hai Plain is the most important region for grain production in China. In this area, long-term rotary tillage in winter wheat and no tillage in summer maize have significantly increased soil bulk density, which impede maize root growth and reduce the grain yield. Subsoiling tillage is an effective practice to improve soil properties and crop growth. The objective of this study was to investigate the integrated effects of subsoiling tillage in both winter wheat and summer maize seasons on soil bulk density, maize root growth and spatial distribution. A two-year field experiment was conducted in winter wheat–summer maize rotation system. Tillage treatments included rotary tillage (RT) and subsoiling tillage (ST) in wheat season, and no tillage (NT), inter-row subsoiling tillage (STIR), and on-row subsoiling tillage (STOR) in maize season. It was found that in the second year, i.e., in 2018, ST decreased soil bulk density by 3.87% and increased porosity by 5.86% at 30–40 cm soil depth at maize maturity. Meanwhile, maize root length density at 40–50 cm depth increased by 30.00% and grain yield increased by 4.70% under ST. In maize season tillage treatments, STOR decreased soil bulk density by 4.52% and increased soil porosity by 6.96% at 20–30 cm soil depth. Compared with NT, the STOR significantly increased maize root length density at 20–30 cm soil depth by 78.45%, and increased root length density in a horizontal area 0–10 cm for both years, with a significant increase of 58.89% in 2018. Therefore, this study demonstrated that in the Huang-Huai-Hai Plain, which has a tidal soil type, subsoiling tillage in winter wheat season and on-row subsoiling tillage in maize season can loosen the soil and improve vertical extension of maize root system in the soil.

Keywords: grain yield; root spatial distribution; subsoiling; soil bulk density; *Zea mays* L.



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1. Introduction

Maize (*Zea mays* L.) is a cereal crop that is grown worldwide [1]. Some countries have used maize as a staple food that is mainly used for forage, glucose, and other by-products [2]. In China, about 31% of its total maize planting area is distributed in the Huang-Huai-Hai Plain [3]. In this region, winter wheat–summer maize double cropping is a typical rotation system, and the conventional tillage methods are rotary tillage in the winter wheat season and no tillage in the summer maize season [4]. However, long-term such tillage system has caused a widespread plow pan. In the northern region of the Huang-Huai-Hai plain, the topsoil average thickness is 14.74 cm, and the plow pan with a bulk density of 1.6 g cm^{−3} is mainly distributed from 15 to 35 cm [5,6]. The increased bulk density is much higher than the optimal soil bulk density for maize growth and development (1.1–1.3 g cm^{−3}) [7], which restricts root growth and soil nutrients uptake by plants [8,9]. The long-term shallow rotation tillage of winter wheat and no tillage of summer maize have caused significant elevations in the plow pans and deterioration of soil properties.

Maize yield largely depends on root growth, especially on the optimization of root structure, which enables roots to absorb more nutrients and water [10–12]. Qi et al. have reported that increasing root distribution in deeper soil layer was beneficial to increase yield [13]. Soil bulk density and porosity are important physical properties of soil and significantly affect the morphology and spatial distribution of the root system [14,15]. High soil bulk density and plow pan impede crop root growth, cause roots mostly distributed in the topsoil layer and reduce the grain yield [16–18]. Therefore, how to improve the soil compaction and optimize the spatial distribution of the maize root system through reasonable tillage measures has become an urgent problem to be solved.

As a conservation tillage, compared with conventional tillage (e.g., rotary tillage), subsoiling tillage is conducive to breaking soil plough pan, reducing soil bulk density and increasing soil porosity [19]. Kong et al. found that the soil bulk density at 0–35 cm depth under subsoiling tillage in maize season was 6.5% lower than that under rotary tillage and 8.8% lower than that under no tillage [20]. Currently, there is some information regarding the effects of subsoiling on root growth [21,22]. Varsa et al. found that maize root length density with subsoiling tillage increased by 10.3 to 17.9% within 20 to 100 cm soil depth [23]. Sun et al. reported that subsoiling tillage increased root dry weight density by 20.1 to 40.7% in 10 to 50 cm soil depth [24]. Although the effect of subsoiling tillage on vertical distribution of roots has been studied, research information on the horizontal distribution of roots is still lacking, and few studies have indicated the integrated effects of tillage conducted in both winter wheat and summer maize season on the spatial distribution of maize root.

In this study, we hypothesized that subsoiling tillage in both winter wheat and summer maize seasons, especially with on-row subsoiling in maize, can loosen the soil and promote maize root growth in both the horizontal and vertical directions. The objective of this study was to investigate the integrated effects of different tillage practices in both winter wheat and summer maize on soil compaction, maize root growth and spatial distribution and to determine the optimal tillage system in this area.

2. Materials and Methods

2.1. Experiment Site Description

Field experiments were conducted at Jiaozhou (36°08' N, 119°54' E), Shandong Province, China, in the periods 2016–2017 and 2017–2018 under a winter wheat–summer maize rotation system. The site has a semi-humid and warm-temperate climate with 210 frost-free days annually. The summer maize season is from late June to early October. Total rainfall during the summer maize season was 426 mm in 2017 and 307 mm in 2018. The average temperature during the summer maize growing season was 24.9 °C in 2017 and 25.1 °C in 2018. In the experimental field, the soil type is categorized as a tidal soil. Soil physical and chemical properties in 0–20 cm soil depth were investigated prior to tillage implementation (Table 1).

Table 1. Selected soil properties at the 0–20 cm soil depth.

Soil Parameter	Soil Depth (0–20 cm)
Bulk density (g cm ^{−3})	1.39
Soil porosity (%)	47.55
Organic matter (g kg ^{−1})	16.58
Total N (g kg ^{−1})	0.94
Available P (mg kg ^{−1})	104.28
Available K (mg kg ^{−1})	162.85

The experiment was laid out in a split-plot design with three replications. Main plots were rotary tillage (RT) and subsoiling tillage (ST) in the winter wheat season, and subsidiary plots were no tillage (NT), inter-row subsoiling tillage (STIR) and on-row subsoiling tillage (STOR) in the summer maize season. The specific tillage practice pattern

in the winter wheat season was as follows: (1) rotary tillage (RT): rotary tiller rotating once to a depth of 15 cm; (2) subsoiling tillage (ST): vibration subsoiler subsoiling once to a depth of 35 cm. The subsoiling tillage pattern in the maize season was as follows: (1) no tillage (NT): direct sowing maize with a no tillage seeder; (2) inter-row subsoiling tillage (STIR): vibration subsoiler subsoiling once to a depth of 35 cm and then sowing maize between subsoiling belts; (3) on-row subsoiling tillage (STOR): vibration subsoiler subsoiling once to a depth of 35 cm, and then sowing maize on subsoiling belts. The summer maize variety WeiKe 702 was planted with population density of 70,500 plants ha⁻¹ with a 70 cm row spacing. Maize was sown on 19 June 2017 and 20 June 2018, and harvested on 10 October 2017 and October 6, 2018. In 2017, in the maize season, fertilizer was applied four times, including one application before sowing and three applications during growing season. Nitrogen, phosphate (P₂O₅), and potassium (K₂O) rates were 240, 90, and 90 kg ha⁻¹, respectively. In 2018, fertilizers were applied three times, one application before sowing and two applications during growing season. Nitrogen, phosphate (P₂O₅), and potassium (K₂O) rates were 180, 90, and 90 kg ha⁻¹, respectively. Irrigation was applied at critical stages four times (total 55 mm) in 2017 and three times (total 68 mm) in 2018.

2.2. Soil Bulk Density and Porosity Measurements

The soil bulk density (g cm⁻³) and porosity (%) were measured according to the cutting-ring method (Doran and Jones, 1996). Soil bulk density and soil porosity were calculated following the equation: Soil bulk density (g cm⁻³) = soil dry weight (g)/cutting-ring volume (cm³); soil porosity (%) = (1 soil bulk density/soil specific gravity) × 100. Measurements were made at different soil depths (0–10, 10–20, 20–30, 30–40, and 40–50 cm) at the seedling stage and maturity stage. The measurements were repeated three times in each plot. Graphics on distribution of soil bulk density and porosity were obtained with Sigmaplot 12.5 software (Systat Software Inc., Chicago, IL, USA).

2.3. Root Measurements

Roots were sampled from soil when maize plants were at the flowering stage. Using the plant as the center of the sampled soil profile, the direction perpendicular to the planted row was designated as the x-axis, and the soil depth as the y-axis. The samples on a horizontal direction (x-axis) were divided into five sections (0–10, 10–20, 20–50, 50–60, and 60–70 cm), with widths of 20 cm and depths of 20 cm. The vertical directions (y axis) were divided into five soil depths (0–10, 10–20, 20–30, 30–40, and 40–50 cm). Soils were excavated using a shovel and were stored in a 40-mesh net bag. Roots were washed free of soil and then frozen at −5 °C.

Each root sample image was obtained using a Epson V700 scanner (Epson, Suzhou, China), and analyzed with the WinRHIZO Pro2017 version 7.6.5 software (Regent Instruments Inc., Toronto, Canada). The dry weight of the roots was determined after drying in an oven at 80 °C to a constant weight. Graphics on the spatial distribution of root surface area density, root length density and root dry weight density were obtained with Surfer11.0 software (Golden Software Inc., Golden, CO, USA).

2.4. Yield

Maize grain yield was determined at maturity stage by harvesting twenty consecutive plants from three rows with uniform growth. Grains were dried at 75 °C and weighed, and yield was recorded at 14% grain moisture.

2.5. Data Analysis

Analysis of variance (ANOVA) and multiple comparisons were performed using SAS statistical software (SAS Institute Inc., Cary, NC, USA). All combined effects of soil depth, tillage method on soil compaction and root distribution of summer maize were examined by three-way ANOVA. Means were compared using Duncan's new multiple range test at $p < 0.05$.

3. Results

3.1. Soil Bulk Density and Porosity

Tillage practices in wheat season affected soil bulk density and porosity in 2018. Soil bulk density at a depth of 10–20 cm under ST was 7.6% higher than that under RT at seedling stage. At maturity, soil bulk density at a depth of 30–40 cm under ST was 3.87% lower than that under RT ($p < 0.05$) (Figure 1a). At the seedling stage, soil porosity at 10–20 cm depth under ST was 12.14% lower than that under RT ($p < 0.05$). At the maturity stage, soil porosity at a depth of 30–40 cm under ST was 5.86% higher than that under RT ($p < 0.05$) (Figure 2a). Tillage practices during maize season affected soil bulk density at maturity. In 2017, soil bulk density at a depth of 30–50 cm under STIR was 3.70% lower than that under STOR ($p < 0.05$). In 2018, STOR treatment decreased soil bulk density at a depth of 20–30 cm by 4.52% compared with NT ($p < 0.05$) (Figure 1b). In 2017, soil porosity of deeper soil (40–50 cm) at maturity was affected by tillage practices in maize season and was 4.05% higher under STIR than under STOR ($p < 0.05$). In 2018, compared with NT, STIR increased soil porosity at a depth of 10–20 cm by 9.86%, and STOR increased soil porosity at a depth of 20–30 cm by 6.96% ($p < 0.05$) (Figure 2b). This study demonstrated that ST in wheat season and STOR in maize season decreased the soil bulk density and increased the soil porosity.

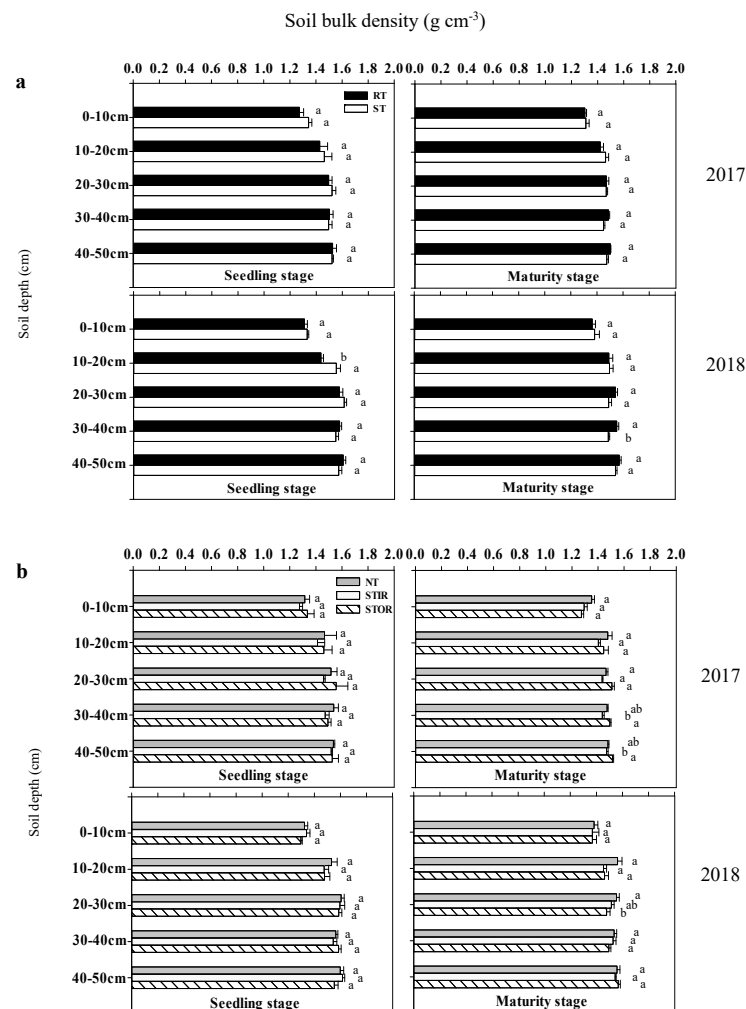
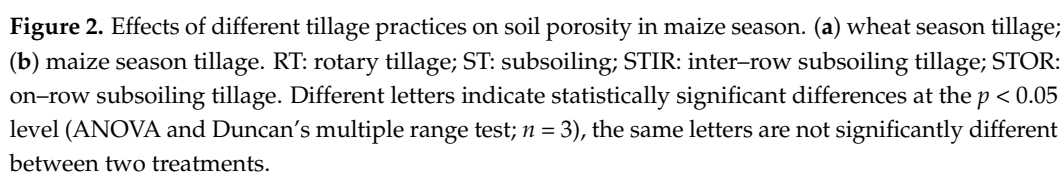


Figure 1. Effects of different tillage practices on soil bulk density in maize season. (a) wheat season tillage; (b) maize season tillage. RT: rotary tillage; ST: subsoiling tillage; STIR: inter-row subsoiling tillage; STOR: on-row subsoiling tillage. Different letters indicate statistically significant differences at the $p < 0.05$ level (ANOVA and Duncan's multiple range test; $n = 3$), the same letters are not significantly different between two treatments.



For the vertical distribution of root dry weight density, the effect of wheat season tillage on root dry weight density was not significant in 2017. However, root dry weight density under ST was 13.28% lower than that under RT in 2018 ($p < 0.05$) (Figure 3a). Under the tillage in maize season, the STOR increased root dry weight density at 10–20 cm depth as compared with NT in both years. The root dry weight density under STOR increased by

50.59% in 2017 and by 20.75% in 2018 ($p < 0.05$). The STIR treatment decreased root dry weight density at 0–10 cm depth by 14.71% in 2018 ($p < 0.05$) (Figure 3b).

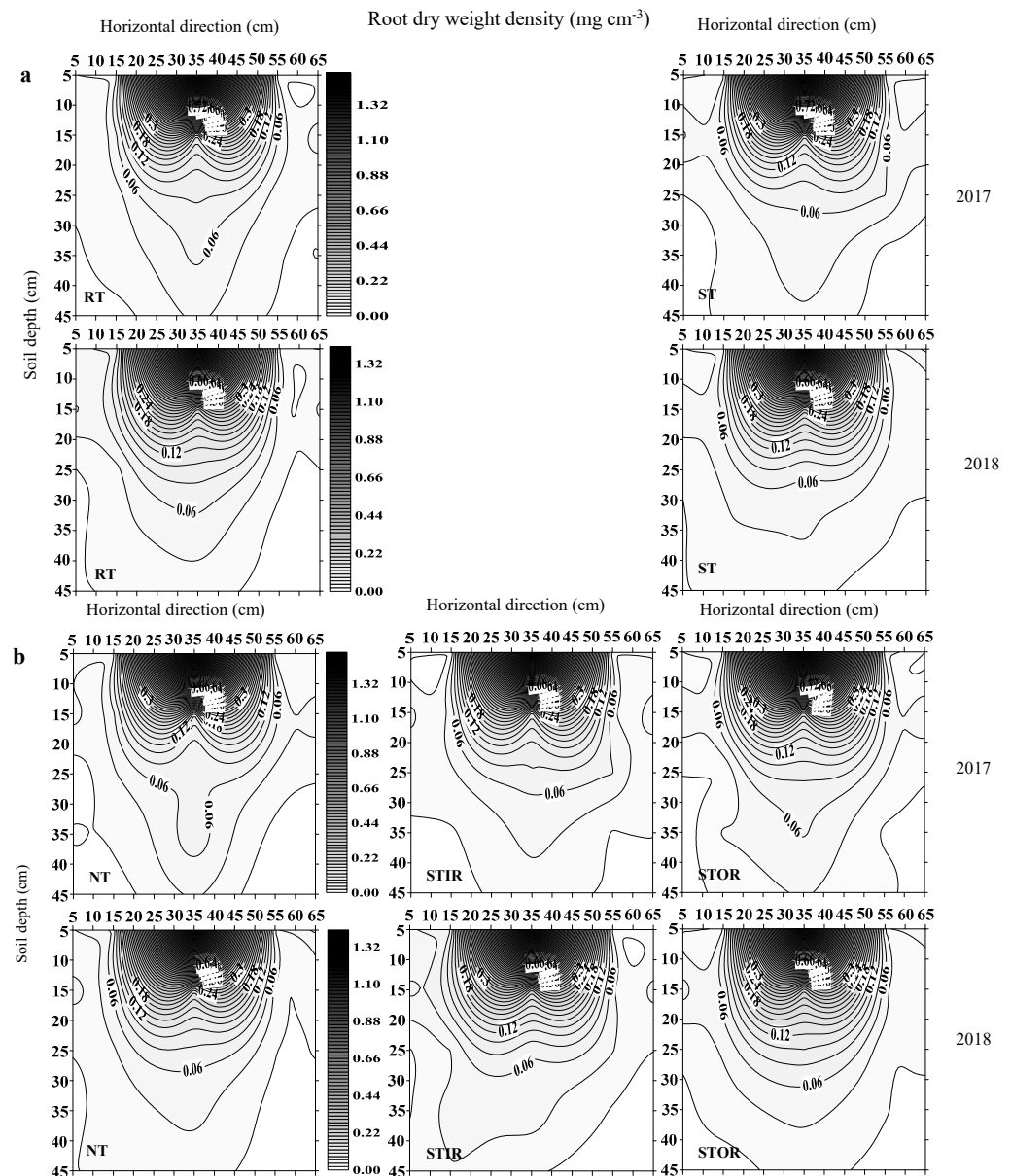


Figure 3. Effects of different tillage practices on root dry weight density in maize at the flowering stage. (a) wheat season tillage; (b) maize season tillage. RT: rotary tillage; ST: subsoiling tillage; STIR: inter-row subsoiling tillage; STOR: on-row subsoiling tillage.

For the horizontal distribution (at 0–20 cm depth) of root dry weight density, the effect of tillage in wheat season on maize root dry weight density was not significant in 2017. However, in 2018, root dry weight density in horizontal areas of 0–10 cm and 20–50 cm from the plant center was both affected by tillage practices in wheat season. The value under ST was lower than that under RT, by 28.07% and 11.76%, respectively ($p < 0.05$) (Figure 3a). Under maize season tillage, compared with NT, STIR decreased root dry weight density at 20–50 cm horizontal area for both years, with a 11.31% decrease in 2018 ($p < 0.05$). STIR also decreased root dry weight density by 14.71% at 0–10 cm horizontal area in 2018 ($p < 0.05$) (Figure 3b).

For the vertical distribution of root length density, the root length density at 40–50 cm depth under ST in wheat season was higher than that under RT for both years, with a

significant increase of 30.00% in 2018 ($p < 0.05$) (Figure 4a). Under the tillage practices in maize season, compared with NT, the STOR increased root length density at a depth of 10–20 cm for both years, with an increase of 51.79% in 2017 ($p < 0.05$). In 2018, both STIR and STOR significantly increased the root length of maize at 20–30 cm depth by 52.59% and 78.45%, respectively ($p < 0.05$) (Figure 4b). For the horizontal distribution, the root length density in a horizontal area of 10–20 cm from the plant center under ST in wheat season was lower than that under RT for both years, with a decrease of 24.90% in 2018 ($p < 0.05$) (Figure 4a). Under the tillage practices in maize season, compared with NT, the STOR increased the root length density in a horizontal area 0–10 cm for both years, with a significant increase of 58.89% in 2018 ($p < 0.05$). STIR increased the root length density in a horizontal area of 10–20 cm by 38.63% in 2018 ($p < 0.05$) (Figure 4b).

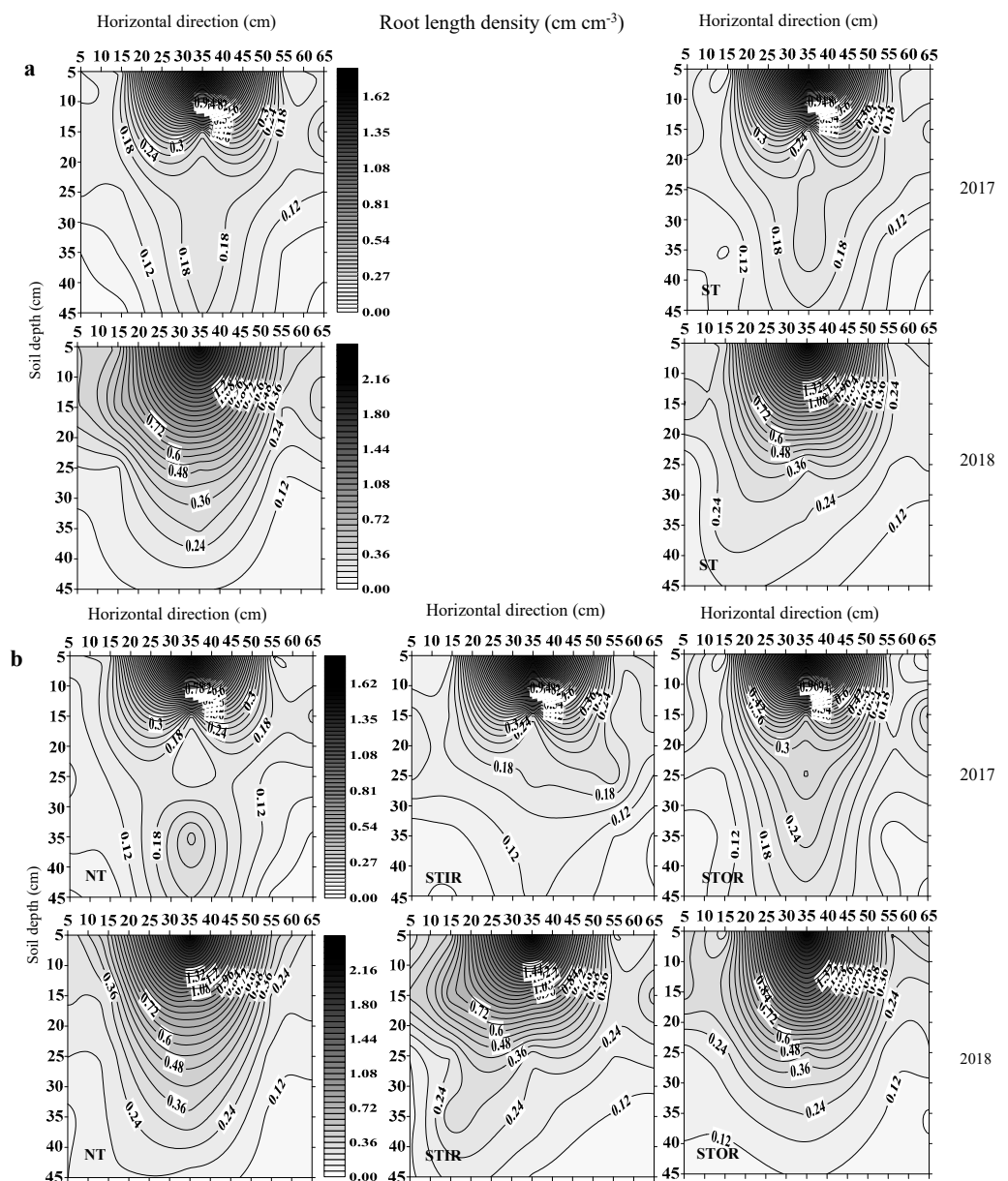


Figure 4. Effect of different tillage practices on root length density of maize at the flowering stage. (a) wheat season tillage; (b) maize season tillage. RT: rotary tillage; ST: subsoiling tillage; STIR: inter-row subsoiling tillage; STOR: on-row subsoiling tillage.

For the vertical distribution of root surface area density, neither of the tillage practices in either the wheat season or the maize season affected root surface area density for both

years (Figure 5). For the horizontal distribution, the root surface area was not affected by the tillage practices in wheat season for both years (Figure 5a). Under the tillage in maize season, the root surface area density was not affected by the tillage practice in 2017. However, in 2018, compared with NT, the STOR increased the root surface area at 0–10 cm by 47.22%, and the STIR increased the root surface area at 10–20 cm by 35.00% ($p < 0.05$) (Figure 5b).

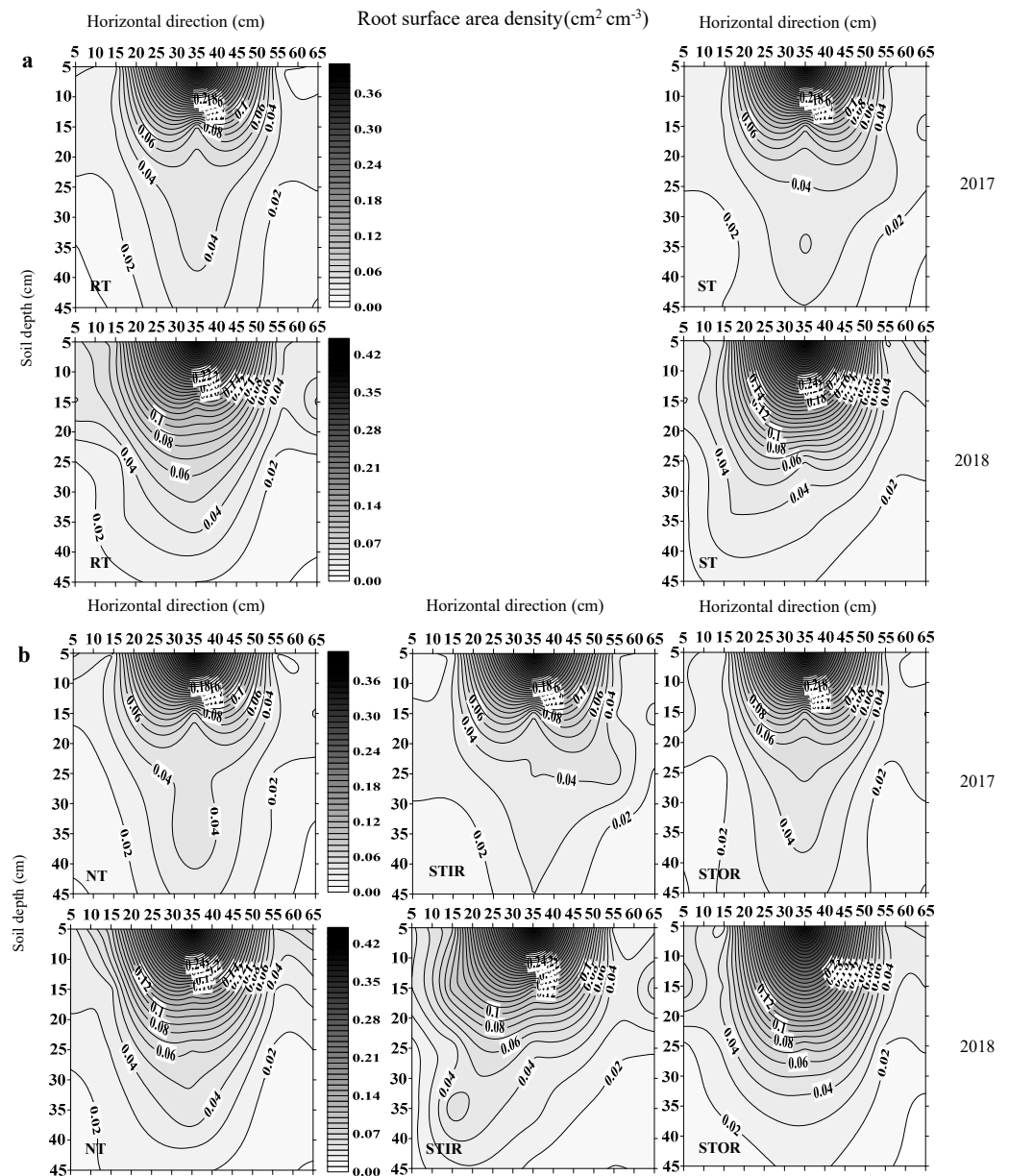


Figure 5. Effect of different tillage practices on root surface area density of maize at the flowering stage. (a) wheat season tillage; (b) maize season tillage. RT: rotary tillage; ST: subsoiling tillage; STIR: inter-row subsoiling tillage; STOR: on-row subsoiling tillage.

3.3. Grain Yield and Aboveground Dry Weight

Under RT tillage in wheat season, grain yield was not affected by maize season tillage practices in 2018, however, in 2017 the grain yield under STIR was significantly lower than NT and STOR treatments by 14.3% and 15.8%, respectively (Table 2). Under ST tillage in wheat season, grain yield was not affected by maize season tillage practices in both years. On average, there were significant differences between RT and ST tillage practices in 2018,

where the average yield under ST was higher than that under RT by 4.70%, while there were no differences among tillage practices (NT, STIR, STOR) in maize season. Under RT tillage in wheat season, above ground dry matter was not affected by maize season tillage practices in both years. Under ST tillage in wheat season, the dry matter under NT was significantly lower than STOR treatment by 11.1% in 2017. On average, the above ground dry matter of maize at the maturity was not affected by tillage practices in either wheat season or maize season for two consecutive years.

Table 2. Effects of different tillage practices on yield and total dry weight at different stages of summer maize season.

Winter Wheat	Summer Maize	Yield (kg ha ⁻¹)		Total Dry Weight (kg ha ⁻¹)	
		2017	2018	2017	2018
RT	NT	11,493 a	8919 a	23,019 a	20,131 a
	STIR	9854 b	9167 a	22,128 a	17,970 a
	STOR	11,698 a	8681 a	21,010 a	19,967 a
ST	NT	11,590 a	9266 a	21,465 b	21,697 a
	STIR	11,407 a	9238 a	22,384 ab	22,120 a
	STOR	11,198 a	9519 a	24,147 a	19,356 a
Average					
RT		11,015 a	8922 b	22,052 a	19,356 a
ST		11,399 a	9341 a	22,665 a	21,058 a
	NT	11,542 a	9092 a	22,242 a	20,914 a
	STIR	10,631 a	9202 a	22,256 a	20,045 a
	STOR	11,448 a	9100 a	22,578 a	19,662 a

Means sharing a common letter within the same column are not significantly different. Different letters indicate statistically significant differences at $p < 0.05$. RT: rotary tillage; ST: subsoiling tillage; NT: no tillage; STIR: inter-row subsoiling tillage; STOR: on-row subsoiling tillage.

4. Discussion

4.1. Soil Bulk Density and Soil Porosity

Soil bulk density is one of the most important soil physical properties. It is a common index reflecting soil compaction in tillage experiments [25]. Although soil bulk density changes throughout a crop growing season, the difference between tillage methods may remain significant in soil bulk density for a long time after tillage [26]. This study showed that the soil bulk density was not significantly influenced by tillage methods conducted either in the wheat or the maize seasons in 2017. However, in 2018, the soil bulk density of 10–20 cm soil layer at the maize seedling stage and 30–40 cm soil layer at the maize maturity stage were significantly affected by tillage practices in the wheat season. Previous research showed that the subsoiling tillage in the wheat season significantly decreased the soil bulk density of the 10–30 cm soil layer at the maturity stage of maize [22]. In this study, at the maize maturity stage, the soil bulk density at 30–40 cm soil layer under ST was 3.87% lower than that under RT conducted in wheat season, and that at the 20–30 cm soil layer under STOR was 4.52% lower than under NT conducted in the maize season. Wang et al. also found that subsoiling tillage significantly reduced soil bulk density at the 0–30 cm soil layer as compared with rotary tillage and no tillage in maize season [27].

Soil porosity is a very important component of soil structure, and has an important impact on soil moisture, air flow, biological activities and root growth. Soil porosity is directly affected by soil bulk density [28,29]. Subsoiling could reduce soil compaction and increase soil porosity [29]. Previous research has found that the porosity of pre-wheat subsoiled soils could be increased by 0.27–3.67% [30]. The results of this study were consistent with previous studies. In this study, at the maize maturity stage, the soil porosity at the 30–40 cm layer under ST in wheat season was 5.85% higher than under RT, and the soil porosity at the 20–30 cm soil layer under STOR in maize season was significantly 6.96% higher than that under NT.

4.2. Root Distribution

Maize roots grown mainly at the 0–50 cm soil layer. Long-term shallow rotary tillage could induce plough pan upward moving and increase soil compaction. As a result, most roots are concentrated in the upper soil layer [31–33]. In this situation, reasonable tillage could improve root growth [34–36]. Previous research has demonstrated that subsoiling tillage in wheat season could significantly increase root dry weight density at the 0–50 cm soil layer [22]. In this study, root length density at the 40–50 cm soil layer in the vertical direction was significantly affected by wheat season tillage and subsoiling increased root length density at the 40–50 cm soil layer for two consecutive years, with an increase of 30%. However, there was no significant difference in root length density at the 40–50 cm soil layer between tillage treatments in the maize season. Although STIR reduced root dry weight density at the 0–10 cm soil layer, it had no significant effect on root density at the 10–50 cm soil layer, which was inconsistent with the previous research results. Sun et al. found that subsoiling tillage could affect root distribution, significantly reduced root dry weight density at the 0–10 cm soil layer, and significantly increased root dry weight density at the 10–50 cm soil layer [24]. This might be due to the different farming machinery and soil texture. At the maize flowering stage, the root length density and root surface area density in the horizontal distribution (vertical 0–20 cm depth) were significantly affected by tillage in the maize season. The STIR and STOR promoted the outward extension of the root system (vertical, at 0–20 cm soil depth). However, Wang et al. found that subsoiling during the maize season could make the root system relatively concentrated in its horizontal distribution, which might be related to different subsoiling methods [27].

4.3. Grain Yield and Total Dry Weight of Summer Maize

The change of the soil physical properties by tillage practices could affect the growth of maize root system and further affect the yield. Mu et al. found that subsoiling tillage in winter wheat season could significantly increase summer maize yield. In this study, maize grain yield under ST in winter wheat season was 4.70% higher than under traditional rotation tillage (RT) [22]. Similar results were found that grain yield under wheat season subsoiling was higher than that under rotary tillage [37]. However, maize seasonal tillage had no significant effect on maize yield.

5. Conclusions

Compared with traditional rotary tillage in wheat season, the subsoiling tillage (ST) (especially for more than two years) decreased the soil bulk density and increased the soil porosity in 30–40 cm soil depth at the maize maturity stage. ST also increased the maize root length density at the 40–50 cm soil depth at the flowering stage. Compared with no tillage in maize season, on-row subsoiling tillage in maize season (STOR) (especially for more than two years) reduced the bulk density and increased the porosity in 20–30 cm soil depth at the maize maturity stage and also increased the root length density of maize at 20–30 cm soil depth. Therefore, our results suggest that subsoiling tillage in winter wheat season and on-row subsoiling in maize seasons can loosen the soil, reduce soil compaction and improve root vertical extension. These are promising soil tillage practices for sustainable maize production in the tidal soil region of the Huang-Huai-Hai plain of China.

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