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Effects of winter wheat season tillage on soil properties and yield of summer maize

Yunqi WANG, Yinghua ZHANG*, Zhimin WANG, Hongbin TAO,
Shunli ZHOU, Pu WANG

College of Agronomy and Biotechnology, China Agricultural University, Beijing, P.R. China
**Corresponding author: zhangyh1216@126.com*

ABSTRACT

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The North China Plain (NCP) serves as China's second most important maize production region. Rotary tillage, a popular method used in winter wheat/summer maize systems in the region, has adverse effects on maize production. The current study was conducted to determine whether rotary tillage after subsoiling in the winter wheat season (RS) improves the grain-filling rate and yield of summer maize by decreasing soil bulk density, when compared with rotary tillage (R), in the NCP. The RS treatment decreased soil bulk density and increased soil moisture in the summer maize season when compared with the R treatment. Root number under the RS treatment at 8 collar and silking stages was 22.4–35.3% and 8.0–11.7% greater than under the R treatment, respectively. The RS treatment significantly enhanced the grain-filling rate and grain weight as compared to the R treatment. Yield, thousand grain weight, biomass, and harvest index under the RS treatment were 7.7, 7.2, 2.3 and 5.3% higher than under the R treatment. Thousands grain weight was correlated with soil bulk density and soil moisture after silking. Consequently, the increase in grain weight and yield of summer maize resulted from the decrease in soil bulk density and a consequent increase in soil moisture, root number and grain-filling rate.

Keywords: *Triticum aestivum*; *Zea mays*; cropping system; soil environment; degradation

The dominant cropping system of the North China Plain (NCP) involves rotation of winter wheat and summer maize (Liu et al. 2016), supplied about 29.6% of all food in China, including around half of the wheat production and a third of the maize production (Du et al. 2010), and the growing season for wheat is from mid-October to early June and for maize from mid-June to early October. Rotary tillage sowing of winter wheat and no-till sowing of summer maize has been widely popular for one decade in the NCP, resulting in an increase in soil compaction and a deeper plough pan (Wang et al. 2014, Mu et al. 2016), creating stress in the soil environment that affects summer maize growth. High soil bulk density in subsurface layers impedes root growth of the subsequent crop(s) and causes nutrient and water deficits (Gajri et al. 1992). Subsoiling is a process that breaks the hardpan layer and the compacted layer of soil without turning over the infertile subsoil at the top (Singh et al. 2013) and can improve soil structure by eliminating soil compaction (Shi et al. 2016).

In addition, soil compaction, an important environmental problem, causes physical soil degradation by adversely influencing the hydraulic properties and productivity parameters of soil while affecting root development and nutrient uptake (Parlak and Parlak 2011) and leading to oxygen deficiency, waterlogging and decreasing grain yield (Arvidsson et al. 2012). Heavy compaction results

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in increased soil strength and bulk density down to 0.4 m depth as well as reduced soil available water and local root growth (Souch et al. 2004). The summer maize season is very short with high air temperatures, so no-till sowing is used widely to keep enough time for summer maize growth in the NCP. Therefore, some practical tillage practices performed during the winter wheat season may improve the soil environment for summer maize.

Wang et al. (2015) examined the effects of rotary tillage after subsoiling on winter wheat, while the effects of rotary tillage after subsoiling in the winter wheat season on yield in the summer maize season remain unclear. Therefore, the aim of the current study was to examine the hypothesis that rotary tillage after subsoiling in the winter wheat season (RS) could reduce soil bulk density in the summer maize season by increasing soil moisture and root number, resulting in an increase in the grain-filling rate, compared to rotary tillage (R).

MATERIAL AND METHODS

Experimental site and meteorological conditions. Field experiments were conducted in two years at the Wuqiao Experiment Station of China Agricultural University in Hebei province, China (37°41'N, 116°37'E, 18 m a.s.l.). This experimental field has clay-loam soil. The topsoil (0–40 cm) contained around 11.8 g/kg organic matter, 1.8 g/kg total N, 46.8 mg/kg available P and 76.8 mg/kg available K. During the summer maize growing season, average precipitation was 466.5 mm; average temperatures were 22.8°C from 1992 to 2012. During the summer maize growing season, total precipitation was 375.3 mm in 2011 and 622.8 mm in 2012; averaged temperatures in 2011 and 2012 were 23.1°C and 23.9°C, respectively.

Crop culture and treatments. The experiment involved 2 treatments, rotary tillage (R) and rotary tillage after subsoiling in the winter wheat season (RS), with 4 replicates in each year. Subsoiling was performed at 35-cm depth keeping an interval of 60 cm between rows with a subsoiler in the experimental RS field, and then rotary tillage was performed at 10-cm depth with rotary cultivator in the R and RS fields before sowing winter wheat (on October 15, 2010 and October 13, 2011). After the winter wheat was harvested, a maize cultivar (Zhengdan 958) was sown at a density of 8.25×10^4 plants/ha with no-till on June 16 in both 2011 and 2012. All 4 replicates in all treatments employed 60-cm row spacing in 6 m × 10 m plots. Each plot received 240 kg/ha N as urea, 39.5 kg P/ha as superphosphate and 107.9 kg K/ha as K_2SO_4 before sowing. No fertilizer and no water were applied during growth.

Data collection. Bulk density core samples (5 cm diameter) at depths of 0–5, 5–10, 10–15, 15–20, 20–25, 25–30, 30–35 and 35–40 cm were taken from random locations with 4 replicates to measure soil bulk density, in each year at sowing of summer maize.

Soil moisture (%) was determined gravimetrically at 0, 30, 60 and 110 days after sowing. Soil samples were taken from 0 to 200 cm at 20-cm increments by using a ground auger, and dried at 105°C to a constant weight with 4 replicates. Soil moisture in each layer was recorded as soil percent moisture content. At 8 collar and silking stages, 4 plants including all roots were collected, separated into root and aboveground parts. Each sample was placed in a string mesh bag. The roots in each bag were prepared by washing away the soil and rinsing them thoroughly with tap water; organic debris and other materials were removed by decanting the samples. The root number per layer (The root distributes at lower internodes, and the root number per internode is considered as the root number per layer. From down to up, the lowest layer is considered as the first layer, and then the second layer) was counted, and the sum of root number per layer was the root number per plant. One hundred ears silking on the same day were tagged in each plot. Four tagged ears from each plot were sampled at 10-days intervals from silking to maturity. The grains were removed from 2 rows of the ear, and then dried at 70°C to a constant weight and weighed.

The grain-filling data were fitted using a log-linear equation (Eq. 1) as described by Gasura et al. (2013):

$$W = \frac{A}{(1 + Be^{-kt})^{\frac{1}{N}}} \tag{1}$$

The grain-filling rate (GFR) was calculated using Eq. 2 as the derivative of Eq. (1):

$$GFR = \frac{AkBe^{-kt}}{N(1 + Be^{-kt})^{\left(\frac{N+1}{N}\right)}} \tag{2}$$

Where: W – grain weight (mg); A – final grain weight (mg); t – time after anthesis (d); and *B*, *k* and *N* – coefficients determined by regression.

Table 1. Effects of rotary tillage (R) and subsoiling in the winter wheat season (RS) on soil bulk density from the 0 to 40 cm soil layer at summer maize sowing

Soil depth (cm)	2011			2012		
	R	RS	$LSD_{0.05}$	R	RS	$LSD_{0.05}$
0–5	1.2	1.16	0.07	1.2	1.16	0.12
5–10	1.4	1.31	0.09	1.39	1.31	0.08
10–15	1.47	1.41	0.1	1.49	1.42	0.18
15–20	1.59	1.42	0.16	1.57	1.42	0.09
20–25	1.65	1.47	0.13	1.65	1.46	0.11
25–30	1.58	1.45	0.12	1.56	1.44	0.08
30–35	1.51	1.41	0.07	1.51	1.41	0.14
35–40	1.53	1.51	0.17	1.53	1.52	0.14

Values indicate means of 4 replicates. Least significant difference (*LSD*) at the 5% level of significance

Six plants were harvested from the centre rows in all the plots, separating them into grains and other parts and oven-dried at 70°C until a constant weight. Biomass and harvest index were measured. Yield was determined based on a 10 m^2 area from the central 2 rows of each plot. In both years, 1000 grains were also separated from the cobs. All grains were dried at 70°C for 72 h to determine dry weight.

Statistical analysis. The statistical analysis was performed with the SAS software package (SAS Institute, Inc., Raleigh, USA). Analysis of variance was conducted through the GLM procedure. Differences were judged by the least significant differences test using a 0.05 level of significance. Correlation analysis was finished by PROC CORR procedures.

RESULTS

Soil bulk density increased with increasing depth in the 0–25-cm soil profile, decreased in the 25–35-cm soil profile, and increased again in the 35–40-cm soil profile under both R and RS treatments, in both years (Table 1). Soil bulk density under the RS treatment was lower than under the R treatment in the 0–40-cm soil profile in two years (Table 1). Soil bulk density was correlated with yield, thousand grain weight, biomass and harvest index (Table 2).

Soil moisture under the RS treatment was higher than under the R treatment in the 20–200-cm (especially 0–60-cm) soil profile during 0–110 days after sowing in two years (Figure 1). Specifically, RS resulted in an increase in soil moisture in the

Table 2. Pearson correlation coefficients (*n* = 16) and the level of significance (*P*-value) of soil bulk density (SBD) and soil moisture at summer maize sowing (SMS), soil moisture at silking stages (SMR), soil moisture at physiological maturity (SMM), total root number at the 8 collar (RV), total root number at the silking stage (RR), yield (Y), thousand grain weight (TGW), biomass (B) and harvest index (HI) under rotary tillage (R) and subsoiling in the winter wheat season (RS)

	SMS	SMR	SMM	RV	RR	Y	TGW	B	HI
SBD	−0.83****	−0.64**	−0.92****	−0.61*	−0.85***	−0.33$^{\text{ns}}$	−0.68**	−0.207$^{\text{ns}}$	−0.68**
SMS		0.87****	0.91****	0.72**	0.85****	0.53*	0.77***	0.44$^{\text{ns}}$	0.72**
SMR			0.82****	0.94****	0.89****	0.88****	0.96****	0.83****	0.83****
SMM				0.80***	0.95****	0.56*	0.82***	0.43$^{\text{ns}}$	0.86****
RV12					0.92****	0.94****	0.98****	0.87****	0.90****
RR1						0.74***	0.92****	0.63**	0.92****
Y							0.91****	0.98****	0.76***
TGW								0.85****	0.86****
B									0.63**

$^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$; $^{****}P < 0.0001$; ns – non-significant at $P < 0.05$

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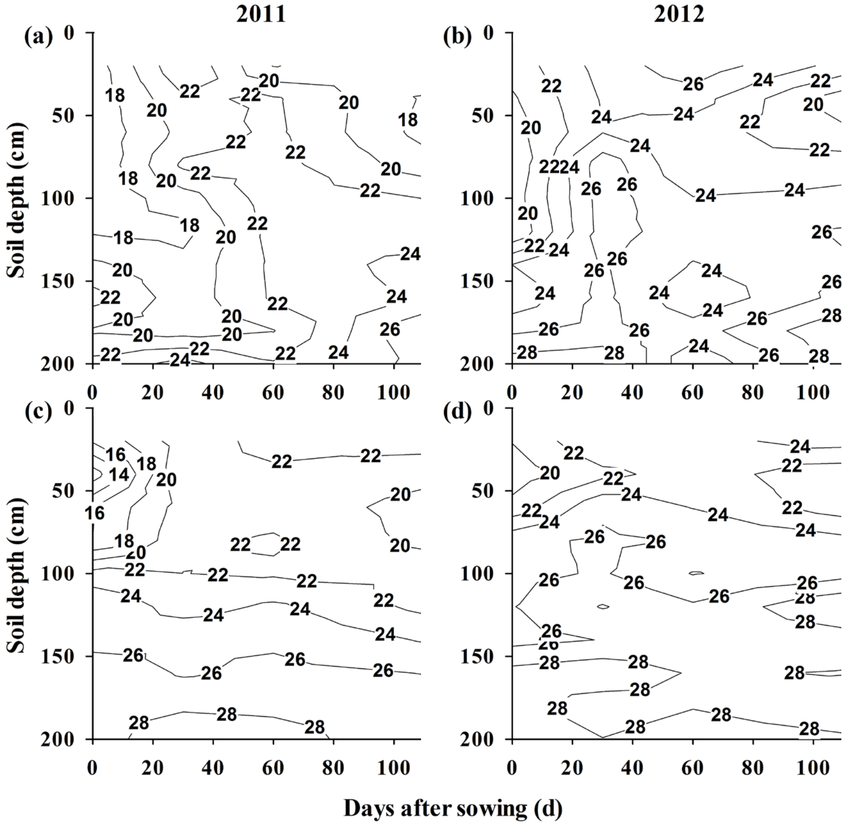

Figure 1. Soil moisture (%) contour map under rotary tillage (R – a, c) and subsoiling in the winter wheat season (RS – b, d)

0–40-cm soil profile in 60 days after sowing under RS compared with the R treatment (Figure 1), due to a decrease in soil bulk density (Table 1). Soil moisture at the silking stage was positively associated with yield, thousand grain weight, biomass and harvest index (Table 2).

Table 3. Effects of rotary tillage (R) and subsoiling in the winter wheat season (RS) on root number per layer and total root number per plant

Growth stage	Root layer number	2011			2012		
		R	RS	$LSD_{0.05}$	R	RS	$LSD_{0.05}$
V8	first	4.5	5.0	0.25	4.4	5.2	0.25
	second	4.5	6.0	0.28	4.7	6.2	0.29
	third	5.3	6.3	0.31	6.1	6.2	0.32
	fourth	6.5	8.2	0.39	7.8	10.0	0.47
	fifth	–	–	–	8.8	11.3	0.54
	total	20.8	25.5	1.23	28.8	39.0	1.82
R1	first	3.8	4.3	0.21	4.6	5.2	0.26
	second	4.2	4.7	0.23	5.6	5.7	0.29
	third	4.5	5.2	0.25	6.3	7.6	0.37
	fourth	7.3	7.5	0.38	8.9	9.4	0.48
	fifth	10.0	11.3	0.56	10.8	12.1	0.60
	sixth	14.3	15.2	0.77	11.8	14.6	0.70
	seventh	15.3	16.0	0.81	15.3	16.0	0.81
	total	59.4	64.2	3.21	63.1	70.6	3.49

Values indicate means of 4 replicates; least significant difference (*LSD*) at the 5% level of significance; V8 – 8 collar stage; R1 – silking stage

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Root number per layer and total root number per plant under the RS treatment were higher than under the R treatment at the 8 collar in both years (Table 3). At the silking stage, root number of the first through seventh root layer and total root number per plant under the RS treatment was 13.0, 12.0, 14.8, 2.3, 13.3, 5.8, 4.9 and 8.0% greater than R in 2011, respectively (Table 3). The RS treatment increased the root number of the first through seventh layer and total root number per plant by 0.67, 0.11, 1.22, 0.56, 1.33, 2.78, 0.75, and 7.4 strips, respectively, compared with the R treatment in 2012 (Table 3). Root number was significantly and positively correlated with yield, thousand grain weight, biomass and harvest index (Table 2).

The thousand grain weight increased rapidly from 10 to 50 days after silking under both tillage practices in two years (Figure 2). As in the case with 2011, the thousand grain weight under the RS treatment at 10, 20, 30, 40 and 50 days after silking was 35.8, 20.4, 5.1, 10.0, and 7.1% higher than in the R treatment in 2012 (Figure 2b). The grain-filling rate rapidly rose from silking to about 30 days after silking, and then quickly decreased for both tillage practices in both growing seasons (Figure 2c, d). The RS treatment evidently increased the grain-filling rate when compared with the R treatment in both years (Figure 2c, d).

Significant differences were detected in yield, thousand grain weight, biomass and harvest index between the R and RS treatments (Table 4). Year (Y) and tillage practice (T) evidently affected yield, thousand grain weight, biomass and harvest index (Table 4). Y × T impressively affected yield and biomass (Table 4). Yield, thousand grain weight, and biomass in 2012 were markedly higher than in 2011, and no significant difference was found in harvest index between the 2 years. Compared with the R treatment, the RS treatment increased yield, thousand grain weight, biomass and harvest index by 7.7, 7.2, 2.3 and 5.3%, respectively (Table 4).

DISCUSSION

Johnson and Tanner (1972) divided yield into 3 components: ear number, kernel number and grain weight. Ear number and kernel number are determined at the plant population, so they are

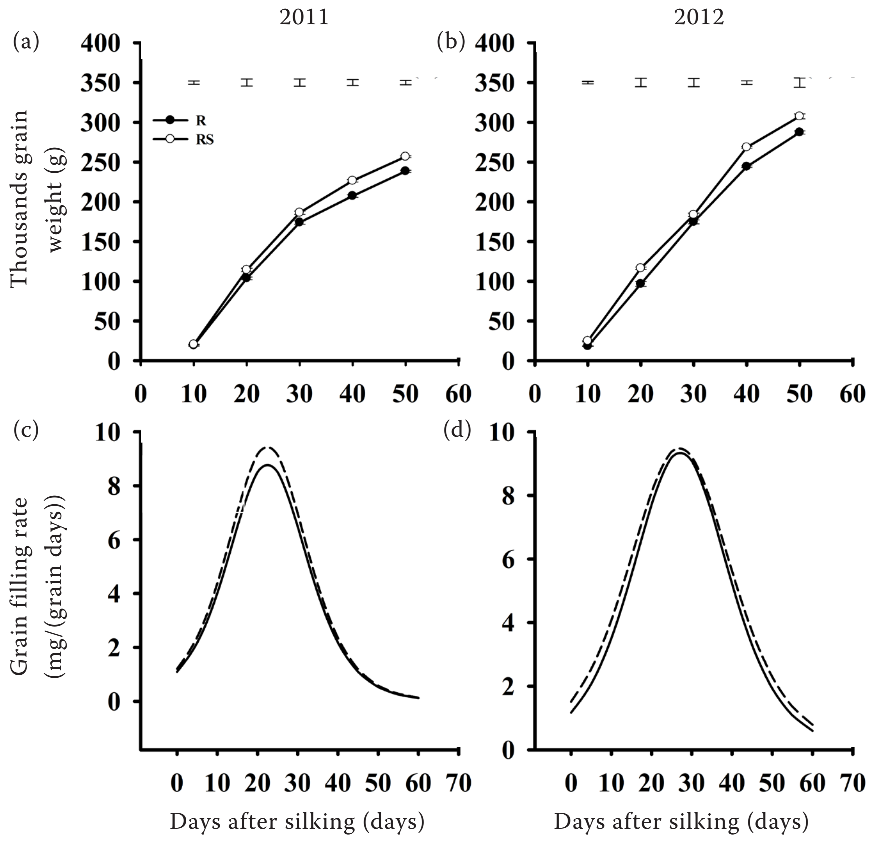

Figure 2. Effects of rotary tillage (R) and subsoiling in the winter wheat season (RS) on thousand grain weight (a, b) and grain-filling ratio (c, d) after silking. Values indicate means of 4 replicates. Vertical bars represent the least significant difference (*LSD*) at the 5% level of significance

Table 4. Effects of rotary tillage (R) and subsoiling in the winter wheat season (RS) on yield (Y, t/ha), thousand grain weight (TGW, g), biomass (B, t/ha) and harvest index (HI, %)

Effect	Y	TGW	B	HI
Year (Y)				
2011	8.9	285.5	16.7	53.3
2012	9.9	309.7	18.3	54.1
$LSD_{0.05}$	0.100	3.446	0.212	0.577
Tillage practice (T)				
R	9.1	287.2	17.3	52.6
RS	9.8	308.0	17.7	55.4
$LSD_{0.05}$	0.100	3.446	0.212	0.577
Y × T				
2011				
R	8.4	276.9	15.9	52.8
RS	8.7	294.2	16.1	54.0
$LSD_{0.05}$	0.089	5.237	0.068	0.566
2012				
R	9.9	297.6	18.6	53.2
RS	10.8	321.7	19.4	55.7
$LSD_{0.05}$	0.206	5.70	0.471	1.165
Source of variation (P)				
Y	< 0.0001	< 0.0001	< 0.0001	< 0.001
T	< 0.0001	< 0.0001	< 0.001	< 0.0001
Y × T	< 0.0001	0.051	0.007	0.024

Least significant difference (*LSD*) at the 5% level of significance

regulated and easily controlled in agricultural practice (Liu et al. 2014). Grain weight potential is largely determined during a long grain filling period (Gambín et al. 2006), and the final grain weight is controlled by the effective period of grain filling (Borrás and Otegui 2001). The grain-filling rate in summer maize may be insufficient if the growth stage is short, or sunshine is inadequate and with an early harvest for the sowing winter wheat in the NCP (Wang et al. 2012). Therefore, grain weight becomes a limited factor affecting an increase in maize productivity and yield in this region.

In this study, the RS treatment significantly decreased soil bulk density in the summer maize season when compared with the R treatment (Table 1). Plant roots easily grow into the deep layer in the loose soil created by subsoiling (Sun et al. 2013). Therefore, root number experiences an evident increase in the RS treatment fields (Table 3). Root system serves as a bridge between the effects of agricultural practices on soil and changes in shoot function and harvested yield (Klepper 1990). Root number was correlated significantly with yield (Table 2). Additionally, the RS treatment markedly enhanced soil moisture in the 0–40-cm soil layer (Figure 1), grain-filling rate and grain weight (Figure 2). Soil moisture at the silking stage was positively correlated with yield and thousand grain weight (Table 2). Consequently, the yield was improved significantly under the RS treatment as compared with R treatment (Table 4).

The yield, thousand grain weight, biomass and harvest index was lower in 2011 than in 2012, which showed that the year affected significantly yield and yield components (Table 4). Two reasons could explain the lower maize yield in 2011 as compared to 2012. The first is that the average temperatures was lower in 2011 (23.1°C) than in 2012 (23.9°C). Temperature is an important ecological factor affecting growth and developments, which further affects the radiation interception rate, and ultimately influences yield of maize (Allison and Daynard 1979). The second is that the precipitation was less in 2011 (375.3 mm) than in 2012 (622.8 mm), which is more favourable for maize growth in 2012.

In the current study, yield, grain weight, biomass and harvest index of summer maize experienced increases of 7.7, 7.2, 2.3 and 5.3% in the RS treatment as compared with R treatment, respectively (Table 4). The grain-filling rate was higher under the RS treatment than the R treatment (Figure 2). These results suggested that rotary tillage after subsoiling in the winter wheat season improved the grain-filling rate and then enhanced grain yield by optimizing the soil environment of summer maize in the NCP.

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