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Effects of subsoiling stage on summer maize water use efficiency and yield in North China Plains

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Abstract: Aiming at the problems of shallow effective soil layering and low utilization rate of precipitation in the North China Plain. The effects of different subsoiling stages on soil physical properties and water use in winter wheat/summer maize fields were studied. Three kinds of tillage treatments were studied: rotary tillage to a depth of 15 cm in October and no-tillage in June (RT), rotary tillage to a depth of 15 cm in October and subsoiling to 35 cm in June (ST-J), subsoiling to a depth of 35 cm in October and no-tillage in June (ST-O). Changes in soil bulk density and soil compaction were consistent over two seasons. Compared to RT, in the 10–50 cm soil layer, ST-J and ST-O decreased the average soil bulk density by 6.18% and 5.66%, respectively, and the soil compaction in the 10–60 cm layer was reduced by 17.89% and 20.50%. ST was improved soil structure and increased the water content of deep soil. The water use efficiency (WUE) of ST-J and ST-O increased by 4.73% and 14.83%, respectively, and the maize yields by 2.90% and 11.35%, respectively. Considering the WUE and maize yields, it was considered that ST-O is more suitable for tillage in the North China Plain.

Keywords: *Zea mays* L.; water storage; soil moisture; weather conditions; soil physics; grain

Winter wheat/summer maize rotation is an important cultivation method in the North China Plain (NCP). Soil cultivation is one of the important basic measures for people to develop and utilize land (Sisti et al. 2004). Good tillage practices can improve soil quality while also protecting the environment and promoting crop growth (Shrivastava and Kumar 2015). Inappropriate tillage and poor timing of field operations decrease the structural stability of soil and create subsoil compaction (Ishaq et al. 2003). Long-term rotary tillage (RT) creates unfavorable soil physical conditions, restrains soil water storage and water use of farmland, and reduces crop yield (Feng et al. 2018). Compared with RT, which completely reverses the soil upper layer by rotating the blade but does not change the structure of the deep soil (Ji et al. 2013), subsoiling tillage (ST) loosens the tillage layer soil structure, improves soil water absorption, and water utilization by crops, thereby improving yield (Mu et al. 2016). ST saves energy and reduces costs (Schneider et al. 2017), and effectively alleviated compaction and recovered soil productivity (Borghei et al. 2008). However, few studies have reported the effects that the timing of tillage and subsoiling have on soil physical properties and crop yield. At the NCP, most farmers are no-tillage in maize season and tillage in wheat season. Subsoiling in June allows summer maize roots to extend deeper into the soil, which increases the plant dry matter (Yu et al. 2013). Wang et al. (2003) and Li et al. (2005) observed that ST showed promise in increasing soil water storage, water use efficiency, and crop yield

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(Sasal et al. 2006). The main objectives of our study were to: (1) explore the synergistic effect of different soil moisture contents and tillage methods on crop water use efficiency (WUE) in a summer maize production system; (2) analyze the effects on soil physical properties; and (3) relate tillage effects on crop yield to measured soil properties, and then choose the appropriate tillage method and stage to increase revenue.

MATERIAL AND METHODS

Site description. This trial was carried out in Shandong province from 2015 to 2018. Winter wheat/summer maize is cultivated throughout the year, and no-till sowing of summer maize is a method generally used in local perennial agriculture. The mean temperature during the experimental period is 25.6°C, and the rainfall levels in the 2017 and 2018 growth periods were 684.70 mm and 535.00 mm, respectively. The experimental field was flat, and the soil was loam (sand 35.2%, silt 46.61%, and clay 18.19%).

Experimental materials. The trial, consisting of three treatments, with three replicates of 10 × 50 m each, was carried out according to the randomized block design. All the treatments, subsoiling tillage in autumn (ST-O) and summer (ST-J), both 35 mm deep, and rotary tillage (RT), were carried out before sowing. ST-O and RT were carried out in the wheat season and no-tillage in the maize season, while ST-J was carried out in the maize season and rotary tillage in the wheat season. The RT consisted of 60 blades (Guangming Model® 1GQN-200, Jiangsu, China) while ST consisted of five shovels (Haofeng Model® 1SF–200, Henan, China) to a depth of 35 cm. Maize was sown with a no-tillage planter (Haofeng Model® 2BMF-12/6, Henan, China). Summer maize cv. Weike 702 was sown in June and harvested in October 2017 and 2018. Spacing between rows and plants was 60 cm and 25 cm, respectively. During the growth periods of each year, 125 kg N/ha, 50.6 kg P/ha, and 83 kg K/ha were used collectively as base fertilizers, and 110 kg N/ha was used as topdressing at the jointing stage.

Measured variables and methods. Soil bulk density was determined by a ring knife after summer maize harvesting, and soil penetration resistance was measured with a penetrometer (CP40-II, Queensland, Australia). The soil three-phase was calculated from the soil water content, bulk density, and total porosity.

Generalized soil structure index and soil three phase structure distance was calculated using the following equation (Wang et al. 2009):

$$GSSI = [(X_S - 25)\ X_L X_G]^{0.4769} \quad (1)$$

$$STPSD = [(X_S - 50)^2 + (X_S - 50)\ (X_L - 25) + (X_L - 25)^2]^{0.5} \quad (2)$$

Where: GSSI – generalized soil structure index; STPSD – soil three phase structure distance; X_S – solid phase volume percentage (> 25%); X_L – liquid phase volume percentage (> 0%); X_G – gas phase volume percentage (> 0%).

Soil moisture content was determined by the soil drilling sampling method.

Seasonal evapotranspiration (ET) for individual plots was determined for each growing season using the soil water balance (Huang et al. 2003):

$$ET = P + \Delta S \quad (3)$$

Where: P – total seasonal precipitation (mm) and ΔS – change in soil water content (mm) from planting to harvest. Since this test did not carry out irrigation during the period, and the absence of large precipitation in the past two years, surface runoff was considered negligible; by measuring, the groundwater level is below 5 m, so we indicated negligible drainage at the site.

Water use efficiency was defined as follows (Li et al. 2010):

$$WUE = Y/ET \quad (4)$$

Where: WUE – water use efficiency for grain yield (kg/m^3); Y – grain yield (kg/m^2); ET – total evapotranspiration (mm).

Yield and yield components. At harvest, yield and yield components were determined in three randomly selected regions of 10 m × 2 rows.

Statistical analyses. The data were processed and statistically analyzed using Excel 2016 (Redmond, USA) and SPSS 20.0 (Chicago, USA). The differences between the means for crop yield and soil properties were determined using the least significant difference (*LSD*).

RESULTS AND DISCUSSION

Soil physical properties. In 2017, the average soil bulk density of RT was 4.8% and 3.6% higher than that of ST-J and ST-O, respectively (Figure 1). However, in 2018, the difference between RT and ST was more significant, as the average bulk density of RT was 6.2% and 6.0% higher than that of ST-J and ST-O, respectively. In 2018, the bulk density of ST-J was higher than that of ST-O, but the difference was

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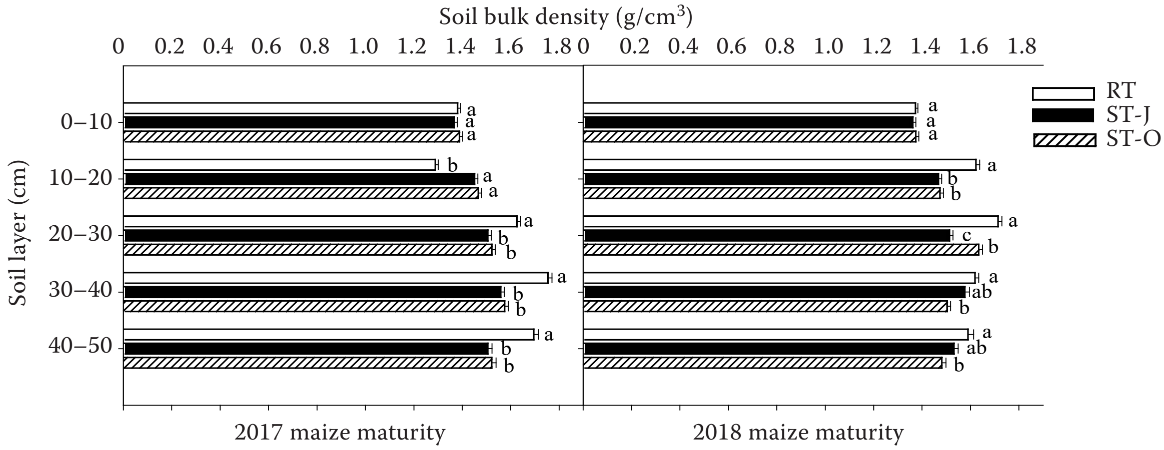

Figure 1. Soil bulk density in 0–50 cm layer under tillage stage. Vertical bars represent standard errors. Different lowercase letters indicate statistical differences among treatments ($P \leq 0.05$). RT – rotary tillage; ST-J – subsoiling in June; ST-O – subsoiling in October

not significant. The physical state of the upper soil layer was susceptible to external factors, including weather conditions (Bryk et al. 2017). ST-J and ST-O are suitable tillage methods that can reduce soil bulk density. However, this was only the result of 2017 and 2018. Whether subsoiling can reduce the soil bulk density in the NCP area for the long-term requires future three-year or long-term tests.

ST was improved soil structure by reducing soil strength and eliminating soil compaction (Wang et al. 2019). Compared with RT, ST-J and ST-O reduced the compaction at the 0–60 cm soil layer by 22.72% and 22.13%, respectively, in 2017 (Figure 2). However, in 2018, the value was reduced to 13.64% and 16.76%, respectively (Figure 2). As shown by Borghei et al. (2008), this was likely because ST alleviated soil compactness in the soil tillage layer, and promoted the elongation of crop roots. The average soil moisture in the 0–30 cm soil layer during the 2017 and 2018 maize harvests

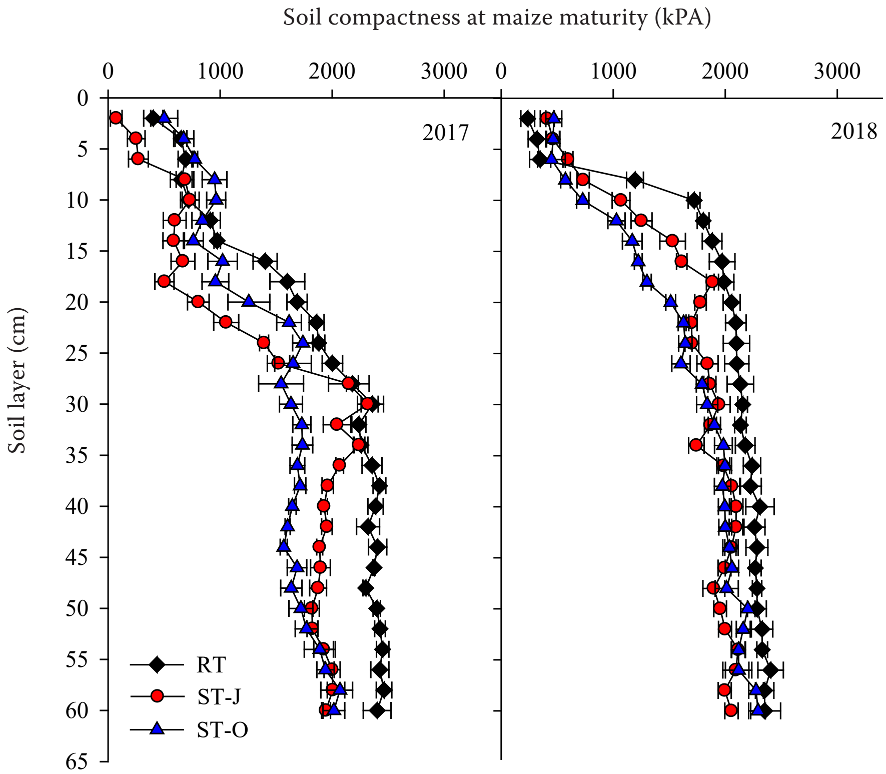

Figure 2. Soil compactness in 0–60 cm layer under tillage stage. Vertical error bars represent standard error of the mean. RT – rotary tillage; ST-J – subsoiling in June; ST-O – subsoiling in October

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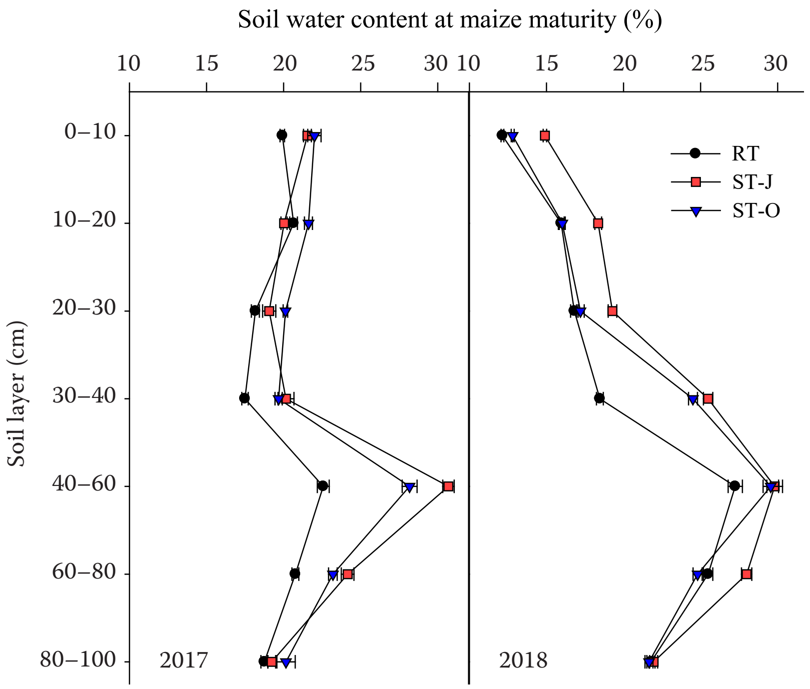

Figure 3. Water content in 0–100 cm layer under tillage stage. Vertical error bars represent standard error of the mean. RT – rotary tillage; ST-J – subsoiling in June; ST-O – subsoiling in October

was 20.35% and 15.95%, respectively (Figure 3). The soil compactness in 2017 was lower than that in 2018, and soil compactness and soil moisture were inversely proportional (Barik et al. 2014).

For most plants, the most suitable condition was that the volume of water and air is approximately equal in the pore space, each accounting for 25% of the total soil volume (Brady and Weil 2007). The closer the three-phase structures of the soil are to the ideal state, the closer the soil three-phase structure distance (STPSD) value is to 0, and the closer the generalized soil structure index (GSSI) is to 100 (Zhang et al. 2015). The gas-phase under different tillage methods showed a downward trend with increasing soil layer depth, while the liquid and solid phases both showed an upward trend (Table 1). In the 20–40 cm soil layer, the average GSSI of ST-J was 3.91% higher, and the average STPSD 2.51% lower than that of ST-O, showing that ST-J had a better effect on deeper soil improvement.

Yield and yield components. In the two years of testing, the yield difference of maize with different subsoiling treatments was obvious, ST-O > ST-J > RT, with significant differences in the effective ear number. ST significantly increased the number of grains per spike, 1000 grain weight of maize, and the final grain yield increased (Mrabet 2011). Due to the high summer precipitation in northern China, especially in severe weather, summer maize is prone to lodging. The soil of ST-J is looser before the jointing stage, so it is more susceptible to high winds and reduces the number of grains ear. Therefore, the effective number of spikes in ST-J was significantly less than in RT and ST-O, but due to the improvement of soil physical indicators by subsoiling, the grain number and grain filling of maize in the late growth stage were improved. The crop yields in 2018, however, were significantly lower than in 2017, and crop yields had a significant negative correlation with precipitation in the growth period (Table 2).

Water use efficiency. Improving the WUE of crops in areas with insufficient water resources is a top priority (Guo et al. 2019). There were significant differences in moisture content among soil layers across the tillage treatments and years (Figure 3). In 2017, ST-J and ST-O increased soil moisture at the 0–100 cm layer, by 14.41% and 6.28%, respectively. ST-J increased soil moisture by 18.98% in the 0–60 cm soil layer, while ST-O only increased it by 10.44% in 2018. The increase in soil water content (30–60 cm) under the three treatments in 2017 and 2018 was ranked in order as follows: ST-J > ST-O > RT. ST-J adjusts the degree of soil compaction to make the soil at the level of 30–40 cm loose and porous, forming a good soil structure.

Compared with rotary tillage, subsoiling broke down the plow sole (Kuang et al. 2020). ET and WUE varied annually, depending on tillage treatment and

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Table 1. Influence of tillage stage on three-phase ratios of soil

Year	Soil layer (cm)	Treatment	Gas-phase	Liquid phase	Solid-phase	GSSI	STPSD
				(%)			
2017	0–10	RT	27.31[b]	20.60[b]	52.09[a]	98.83[a]	3.81[b]
		ST-J	30.64[a]	21.55[a]	47.81[b]	98.27[a]	4.93[a]
		ST-O	27.72[b]	23.67[a]	48.62[b]	99.60[a]	2.35[c]
	10–20	RT	26.98[b]	17.59[c]	55.43[a]	96.32[b]	6.65[a]
		ST-J	29.02[a]	20.03[b]	50.95[b]	98.34[ab]	4.57[b]
		ST-O	25.03[c]	23.43[a]	51.54[b]	99.82[a]	1.55[c]
	20–30	RT	22.07[b]	16.58[a]	61.35[a]	92.62[b]	10.20[a]
		ST-J	28.23[a]	17.07[a]	54.70[c]	95.91[a]	6.90[b]
		ST-O	29.26[a]	13.32[b]	57.42[b]	90.37[c]	10.24[a]
	30–40	RT	11.94[c]	18.12[c]	69.94[a]	79.75[b]	17.55[a]
		ST-J	21.78[a]	20.16[b]	58.06[b]	96.55[a]	7.03[c]
		ST-O	17.05[b]	23.52[a]	59.43[b]	94.28[a]	8.79[b]
2018	0–10	RT	32.42[c]	15.09[a]	52.49[a]	93.11[a]	8.93[b]
		ST-J	34.84[b]	14.90[a]	50.26[a]	91.99[a]	9.97[b]
		ST-O	37.23[a]	12.81[b]	49.96[a]	87.85[b]	12.21[a]
	10–20	RT	24.19[b]	19.73[a]	56.08[a]	97.56[a]	5.72[b]
		ST-J	30.03[a]	18.36[b]	51.61[b]	97.05[ab]	5.99[b]
		ST-O	29.70[a]	16.03[c]	54.27[ab]	94.69[b]	7.77[a]
	20–30	RT	15.67[c]	19.65[a]	64.68[a]	88.94[c]	12.87[a]
		ST-J	23.60[a]	19.29[a]	57.11[b]	96.88[a]	6.53[c]
		ST-O	19.76[b]	17.21[b]	63.03[a]	91.37[b]	11.36[b]
	30–40	RT	9.81[b]	24.40[a]	65.79[a]	79.91[b]	15.50[a]
		ST-J	13.50[a]	25.49[a]	61.01[b]	89.54[a]	11.26[b]
		ST-O	13.29[a]	24.51[a]	62.20[b]	88.6[a]	11.96[b]

Within each factor, different lowercase letters in the same column indicate statistical differences among treatments ($P \leq 0.05$). RT – rotary tillage; ST-J – subsoiling in June; ST-O – subsoiling in October; GSSI – generalized soil structure index; STPSD – soil three-phase structure distance

environmental conditions. Thus, the same ranking was observed for evapotranspiration in both growing seasons, namely: RT > ST-J > ST-O. ET was significantly higher in 2017 than in 2018 (Figure 4). Soil

Table 2. Effects of tillage stage on grain yields and components of summer maize

Year	Treatment	Ear number (10^4 ear/ha)	Grains number per ear (grain/ear)	1000-grain weight (g)	Yield (t/ha)
2017	RT	5.67[c]	564.24[c]	302.52[b]	10.02[c]
	ST-J	5.76[b]	586.34[b]	302.26[b]	10.30[b]
	ST-O	5.81[a]	618.06[a]	304.29[a]	10.96[a]
2018	RT	6.18[a]	477.09[c]	262.51[c]	7.25[c]
	ST-J	5.75[c]	528.43[b]	270.63[b]	7.47[b]
	ST-O	6.14[b]	551.21[a]	274.89[a]	8.27[a]

Within each factor, different lowercase letters in the same column indicate statistical differences among treatments ($P \leq 0.05$). The precipitation during the growth period of maize in 2017 and 2018 was 684.70 mm and 535.00 mm, respectively. RT – rotary tillage; ST-J – subsoiling in June; ST-O – subsoiling in October

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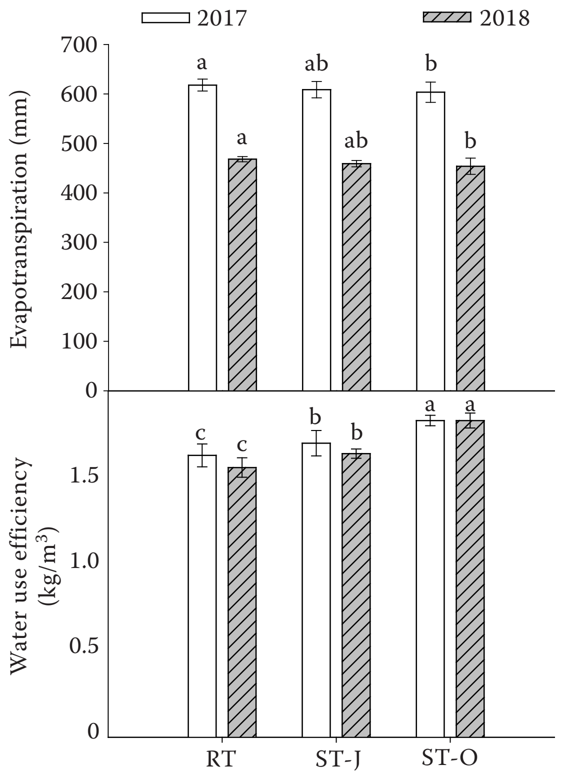

Figure 4. Evapotranspiration and water use efficiency of summer maize in the 2017 and 2018 summer maize growing seasons. Vertical error bars represent standard error of the mean. Different lowercase letters indicate statistical differences among treatments ($P \leq 0.05$). RT – rotary tillage; ST-J – subsoiling in June; ST-O – subsoiling in October

moisture is affected by the growth of the crop and soil evaporation throughout the growing period. WUE in both 2017 and 2018 was higher in ST-O than in ST-J, due to the significantly lower yield of ST-J than of ST-O. Therefore, to improve the WUE in ST-J, it is necessary to increase the yield.

In conclusion, subsoiling broke up plow sole and better water storage. The effect of ST-O on the construction of a reasonable soil layer was more significant, reduced soil bulk density, compactness, and improved WUE. ST-O ensured that summer maize could better fill the grain during the growing period and achieved high and stable yield and reverted the decline of sustainable farmland productivity. ST-O was no-tillage in the summer maize season, which better-reduced soil disturbances and was more suitable for local tillage habits. Therefore, subsoiling in autumn constituted the optimum tillage method for loam in the NCP.

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