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## Effect of subsoiling depth on soil physical properties and summer maize (*Zea mays* L.) yield

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**Abstract:** The present study was carried out in 2016–2017 to assess the effect of subsoiling depth on the soil bulk density, stability of soil structure, soil physical properties and summer maize yield based on a field experiment started in 2015. Four tillage depths were studied: conventional tillage 25 cm (CT<sub>25</sub>); subsoiling tillage 30 cm (ST<sub>30</sub>); subsoiling tillage 35 cm (ST<sub>35</sub>) and subsoiling tillage 40 cm (ST<sub>40</sub>). The results showed that at the 20–50 cm depth ST<sub>30</sub>, ST<sub>35</sub> and ST<sub>40</sub> decreased the mean soil bulk by 4.59, 7.13 and 8.27%, respectively, and at the 0–40 cm depth reduced soil compactness by 17.62, 23.63 and 36.42%, respectively, as compared to CT<sub>25</sub>. ST<sub>40</sub> reduced soil compactness in the 0–40 cm soil layer under conditions of relative drought (during the maize season growing season of 2016), ST<sub>35</sub> and ST<sub>40</sub> increased macroaggregates (> 0.25 mm), improved the stability of the aggregate structure (geometric mean diameter and mean weight diameter) (20–40 cm), increased soil water storage capacity at 40–60 cm and increased maize yield by 7.89% and 8.91%, respectively. Considering the improvement of soil properties and crop yield, ST<sub>35</sub> was the optimum method to increase maize yield and modulate soil physical properties in the North China Plain.

**Keywords:** tillage layer; soil quality; soil compaction; water content; soil depth; grain

Long-term conventional tillage (CT) led to several soil quality problems, such as a shallow soil tillage layer, plough bottom thickening, poor permeable water-holding performance, height water velocity and damaged soil structure (van Wie et al. 2013). However, the same problems existed when the conventional tillage method was used in the North China Plain (NCP) (Chen et al. 2011). Conservation tillage can reduce soil erosion, increase penetration resistance beneath the tilled layer (Liu et al. 2016), while improving water use efficiency and the structural stability of large aggregates and soil structure (Dalal and Chan 2001). A key component of conservation tillage is subsoiling (ST), which reduces soil strength and improves soil properties (Comia et al. 1994). Moreover, ST considerably improves crop yield

(Guan et al. 2014). Therefore, ST is the main tillage system the use of which is reported in the literature (Bogunovic et al. 2018). The structure and thickness of the tilled layer determine the survival environment of crops and the supply of nutrients and water (Castel and Cantero-Martínez 2003). Shallow tillage depth (15–25 cm) makes it difficult to break the soil using the bottom of the plough and is not conducive to crop root growth; greater tillage depth (40–60 cm) does not allow the crop root to absorb fertilizer and decrease the supply of crop nutrients (Han et al. 2015). Thus, tillage depth has an important effect on soil properties and crop yield. However, the effects of ST depth on soil physical properties and crop yields in the NCP have not been previously reported. The main objectives of our study were to: (1) identify ongoing

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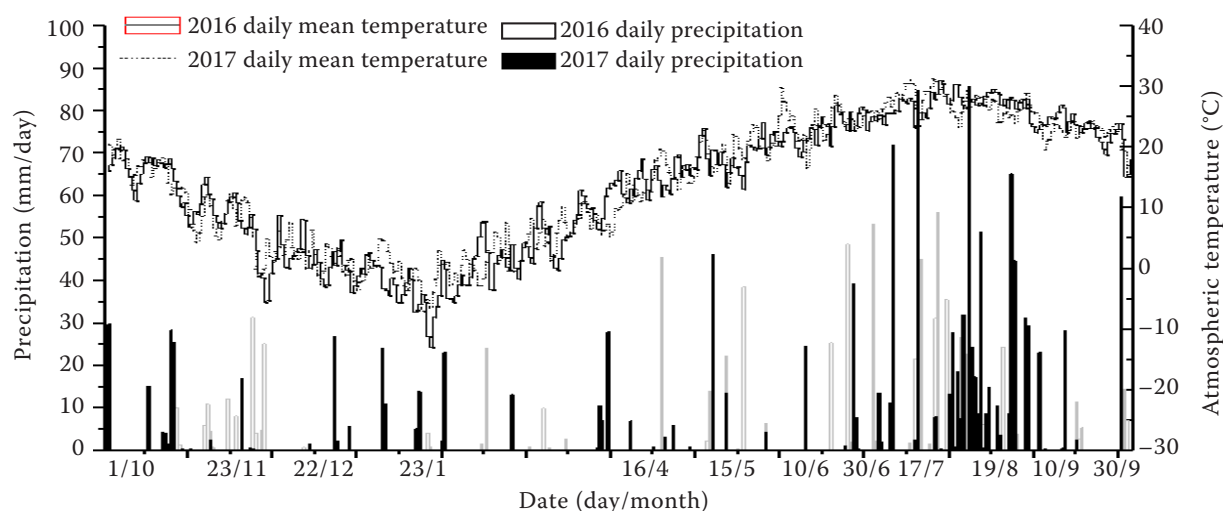


Figure 1. The atmospheric temperature and precipitation at the experimental site during 2016–2017

NCP experiments with tillage depth in subsoiling as an experimental factor; (2) analyze the effects on soil physical properties (soil bulk density, soil compaction, aggregate structure, soil water content); (3) relate tillage effects on crop yield to measured soil properties.

## MATERIAL AND METHODS

**Field site description.** The experiment was conducted in a field in the Shandong province (36°55'59"N, 120°39'33"E) from 2015 to 2017. The daily mean temperature and total precipitation distributions during the experimental period are shown in Figure 1. The crop system consists of winter wheat from October to June and summer maize from June to September. The experimental field was flat and the soil was loam (sand 35.2%, silt 46.61% and clay 18.19%), with pH of 6.79. In the 0–40 cm soil layer, the organic carbon and total N, P and K were 3.47 g/kg, 0.69 g/kg, 35.51 mg/kg and 89.12 mg/kg, respectively.

**Experimental procedure.** The randomized complete block design included four kinds of tillage depth: conventional tillage 25 cm (CT<sub>25</sub>); subsoiling tillage 30 cm (ST<sub>30</sub>); subsoiling tillage 35 cm (ST<sub>35</sub>) and subsoiling tillage 40 cm (ST<sub>40</sub>). The plot size was 8.5 m wide and 50 m long with three replicates. Summer maize

(cv. Wei Ke 702) was sown on June 10 in 2016 and June 8 in 2017. During the maize growth periods, 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. All of the soil tillage practices were performed following the maize harvest. The CT consisted of four ploughings (Bochi Model® FZL–430, Jiangsu, China) while ST consisted of five rotary hoeing's (Haofeng Model® 1SF–200, Henan, China) to 40 cm depth. Maize residues were mechanically shredded and buried using a moldboard plough. Ploughing was carried out on October 12, 2015, with the ploughing depth of 25 cm and ST tillage depths of 30, 35 and 40 cm, and soils of all treatments were subjected to traditional tilling with a depth of 25 cm on October 14, 2016. Table 1 shows that the rainfall levels in the growth periods were 378.2 mm in 2016 and 616.4 mm in 2017.

**Measured variables and methods.** Soil samples were collected after maize harvest on October 1, 2016 and October 4, 2017. The bulk density and soil porosity in the 0–50 cm depth were determined using the core method, soil density approximation to take 2.65 g/cm<sup>3</sup>. Soil penetration resistance was measured (CP40–II, Queensland, Australia). Soil moisture content was determined by drying method and expressed by soil volume

Table 1. Precipitation at all levels of maize (%)

Year	Light rain (> 10 mm)	Moderate rain (10–25 mm)	Heavy rain (25–50 mm)	Cloudburst (50–100 mm)	Total precipitation (mm)
2016	13.33	35.27	36.59	14.81	378.2
2017	6.91	18.05	23.69	51.35	616.4

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Table 2. Analysis of soil physical properties and soil aggregate stability indices of maize as affected by year tillage and soil depth

Source of variation	Soil bulk density	Soil compaction	Volumetric moisture content of soil	$R > 0.25$	Geometric mean diameter	Mean weight diameter
Year (Y)	*	**	**	**	*	*
Tillage (T)	*	**	**	**	**	**
Soil depth (D)	**	**	**	**	**	**
Y × T	ns	**	ns	*	ns	**
Y × D	*	*	**	**	ns	**
T × D	ns	**	**	**	**	**
Y × T × D	ns	**	**	ns	*	*

ns – not significant; \* $P < 0.05$ ; \*\* $P < 0.01$

moisture content and soil aggregates were assessed using the wet sieve method (Oades and Waters 1991). The proportions of aggregates were used to calculate the aggregate content with a diameter of  $> 0.25$  mm  $R_{0.25}$  (Hou et al. 2012) the mean weight diameter (MWD) and the geometric mean diameter (GMD) (Youker and McGuinness 1957). The parameters were calculated as follows:

$$R_{0.25} = \frac{M_{i>0.25}}{M_T}$$

$$MWD = \left[ \frac{\sum_{i=1}^n (x_i w_i)}{\sum_{i=1}^n w_i} \right]$$

$$GMD = \text{Exp} \left[ \frac{\sum_{i=1}^n w_i \ln x_i}{\sum_{i=1}^n w_i} \right]$$

Where:  $R_{0.25}$  – water stability of large aggregates ( $> 0.25$  mm);  $M_{i > 0.25}$  – aggregate content with a diameter of  $> 0.25$  mm, the total weight of  $M_i$  aggregates (g).  $W_i$  – weight of the

aggregates in a specific size range as a proportion of the total dry weight of the analyzed sample;  $n$  – number of sieves;  $X_i$  – mean diameter of aggregates for each sieve size.

Yield samples of maize collected in three 10 m-long middle rows were randomly selected in the central area of each plot to exclude edge effects at maturity.

**Statistical analyses.** The data were statistically analyzed using the SPSS 22.0 (Chicago, USA) statistical analysis system. The differences between the means for crop yield and soil properties were determined using the least significance difference (LSD).

## RESULTS AND DISCUSSION

Soil physical properties were significantly affected by year tillage and soil depth (Table 2). No significant difference was found between CT and ST at the 0–20 cm depth, but soil bulk density increased with soil layer

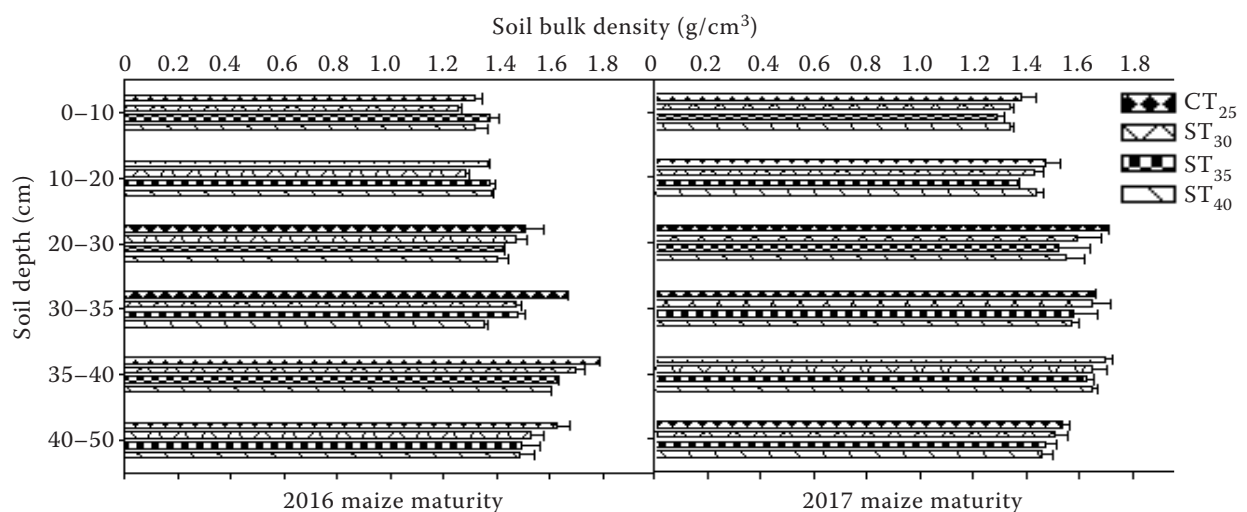


Figure 2. Soil bulk density in 0–50 cm layer under tillage depth. Conventional tillage 25 cm (CT<sub>25</sub>); subsoiling 30 cm (ST<sub>30</sub>); subsoiling 35 cm (ST<sub>35</sub>); subsoiling 40 cm (ST<sub>40</sub>)

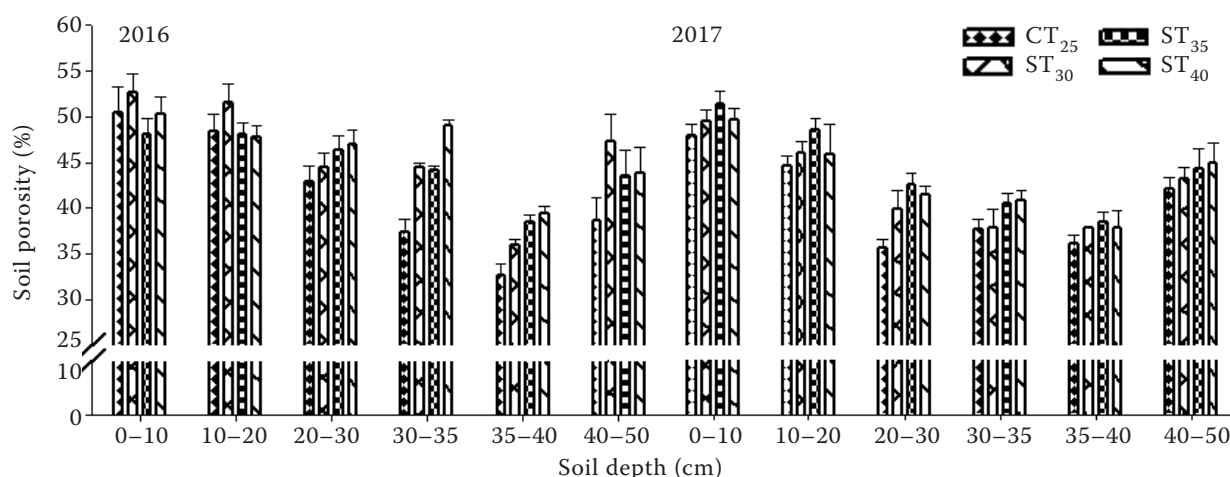


Figure 3. Soil porosity in 0–50 cm layer under tillage depth. Conventional tillage 25 cm ( $CT_{25}$ ); subsoiling 30 cm ( $ST_{30}$ ); subsoiling 35 cm ( $ST_{35}$ ); subsoiling 40 cm ( $ST_{40}$ )

depth (Figure 2). The results show that soil compaction has a significant negative correlation with water content (Ahmadi and Gaur 2015) (Figure 4). The amount of dry stable macroaggregates > 0.25 mm in soil layer of 20–40 cm was significantly increased by ST (Table 3). The soil water content in the crop

growth period differed significantly at tillage depths (Figure 5). This suggests that ST can modulate soil physical properties at 20–40 cm.

**Physical characteristics.** Soil bulk density is an index of physical properties of soil that reflects the compactness of soil layers. Compared with  $CT_{25}$ ,

Table 3. Soil aggregate stability indices ( $R > 0.25$ , geometric mean diameter (GMD) and mean weight diameter (MWD)) under different tillage depth systems in 0–40 cm layer

Treatment	Depth (cm)	2016			2017		
		$R > 0.25$ mm (%)	GMD (mm)	MWD	$R > 0.25$ mm (%)	GMD (mm)	MWD
$CT_{25}$	0–10	83.83 <sup>c</sup>	1.41 <sup>a</sup>	2.11 <sup>b</sup>	87.46 <sup>a</sup>	1.29 <sup>c</sup>	2.21 <sup>a</sup>
$ST_{30}$		84.51 <sup>bc</sup>	1.45 <sup>a</sup>	2.90 <sup>a</sup>	90.50 <sup>b</sup>	1.42 <sup>a</sup>	2.51 <sup>a</sup>
$ST_{35}$		86.79 <sup>a</sup>	1.43 <sup>a</sup>	2.47 <sup>a</sup>	88.74 <sup>b</sup>	1.35 <sup>b</sup>	1.68 <sup>b</sup>
$ST_{40}$		81.98 <sup>c</sup>	1.40 <sup>a</sup>	2.03 <sup>b</sup>	87.78 <sup>b</sup>	1.27 <sup>c</sup>	1.72 <sup>b</sup>
$CT_{25}$	10–20	87.59 <sup>a</sup>	1.44 <sup>a</sup>	2.50 <sup>c</sup>	85.17 <sup>a</sup>	1.26 <sup>b</sup>	2.17 <sup>b</sup>
$ST_{30}$		85.44 <sup>a</sup>	1.46 <sup>a</sup>	3.11 <sup>b</sup>	90.89 <sup>b</sup>	1.31 <sup>ab</sup>	1.79 <sup>b</sup>
$ST_{35}$		86.19 <sup>a</sup>	1.46 <sup>a</sup>	3.91 <sup>a</sup>	87.64 <sup>b</sup>	1.44 <sup>a</sup>	2.73 <sup>a</sup>
$ST_{40}$		85.52 <sup>a</sup>	1.44 <sup>a</sup>	2.61 <sup>c</sup>	88.35 <sup>b</sup>	1.41 <sup>a</sup>	2.07 <sup>b</sup>
$CT_{25}$	20–30	79.78 <sup>c</sup>	1.34 <sup>b</sup>	1.62 <sup>b</sup>	83.00 <sup>b</sup>	1.42 <sup>a</sup>	2.35 <sup>b</sup>
$ST_{30}$		87.79 <sup>a</sup>	1.36 <sup>b</sup>	1.75 <sup>b</sup>	84.44 <sup>b</sup>	1.25 <sup>b</sup>	1.55 <sup>c</sup>
$ST_{35}$		80.96 <sup>bc</sup>	1.44 <sup>a</sup>	2.67 <sup>a</sup>	88.09 <sup>a</sup>	1.48 <sup>a</sup>	3.44 <sup>a</sup>
$ST_{40}$		83.02 <sup>b</sup>	1.43 <sup>a</sup>	2.42 <sup>a</sup>	90.87 <sup>a</sup>	1.48 <sup>a</sup>	3.42 <sup>a</sup>
$CT_{25}$	30–40	80.99 <sup>c</sup>	1.28 <sup>b</sup>	1.49 <sup>b</sup>	82.52 <sup>a</sup>	1.35 <sup>ab</sup>	1.58 <sup>b</sup>
$ST_{30}$		83.02 <sup>ab</sup>	1.28 <sup>b</sup>	1.96 <sup>ab</sup>	85.21 <sup>b</sup>	1.44 <sup>a</sup>	2.59 <sup>a</sup>
$ST_{35}$		82.18 <sup>b</sup>	1.26 <sup>b</sup>	2.14 <sup>a</sup>	91.06 <sup>b</sup>	1.42 <sup>a</sup>	2.19 <sup>a</sup>
$ST_{40}$		85.32 <sup>a</sup>	1.43 <sup>a</sup>	2.47 <sup>a</sup>	92.61 <sup>a</sup>	1.48 <sup>b</sup>	2.31 <sup>b</sup>

Within each factor, means in the same column followed by the same letters are not significantly different at  $P < 0.05$  (least significance difference ( $LSD$ ) test); conventional tillage 25 cm ( $CT_{25}$ ); subsoiling 30 cm ( $ST_{30}$ ); subsoiling 35 cm ( $ST_{35}$ ); subsoiling 40 cm ( $ST_{40}$ )

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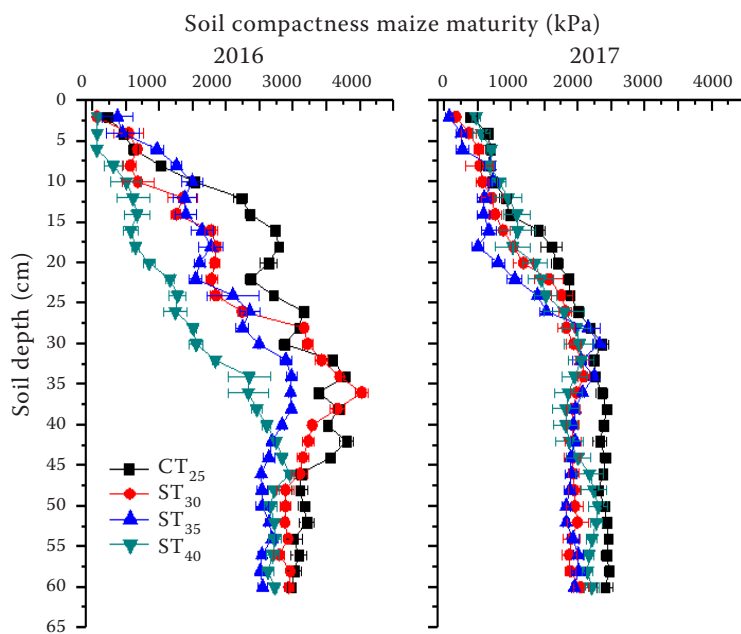


Figure 4. Soil compactness at tillage depths. Conventional tillage 25 cm ( $CT_{25}$ ); subsoiling 30 cm ( $ST_{30}$ ); subsoiling 35 cm ( $ST_{35}$ ); subsoiling 40 cm ( $ST_{40}$ )

$ST_{30}$ ,  $ST_{35}$  and  $ST_{40}$  the mean soil bulk decreased by 4.59, 7.13 and 8.27%, respectively, at the 20–50 cm depth. This indicated that with the increase of subsoiling depth, there was a greater effect on the improvement of soil tillage layer density. The bulk density of the 0–30 cm soil layer in 2017 was higher than that of the same soil layer in 2016, mainly because of the higher amount of precipitation, which increased soil compactness.

Soil bulk density and thus porosity of the investigated soils both differed due to tillage depth (Figure 3). As the total porosity, ST is calculated based on bulk density and default particle density, the tendencies of ST are the same as for the bulk density. Two-year data show that  $ST_{35}$  and  $ST_{40}$  have significant effects on improving soil porosity in soil layer of 30–40 cm. Thus, soil porosity can promote the absorption of water and nutrients in crop roots (Kutílek 2004)

As shown by Pikul and Aase (2003), ST can improve soil structure by reducing soil strength and eliminating soil compaction. Compared with  $CT_{25}$ ,  $ST_{30}$ ,  $ST_{35}$ ,  $ST_{40}$  reduced the compactness by 17.62, 23.63 and 36.42%, respectively, at the 0–40 cm soil layer (Figure 4). This might be because ST improved soil compaction in the soil tillage layer, and thus provided better environment for the growth of crop root and promoted the elongation of crop roots. The root-ligation residues improved the compaction state of traditional soils (Borghesi et al. 2008). The degree of soil compaction in 2017, however, was significantly lower than in 2016 and soil compaction had a significant negative correlation with soil water content (Table 1).

**Soil structure.** Soil aggregate is the foundation of soil structure and site material, energy transformation and metabolism in soil (Six et al. 2000). The MWD is an important evaluation index for soil aggregate stability, with a higher value indicating a better level of soil aggregate stability (Nimmo et al. 2002). The amount of dry stable macroaggregates > 0.25 mm was significantly higher in the 20–40 cm layer with  $ST_{30}$ ,  $ST_{35}$  and  $ST_{40}$  than with  $CT_{25}$  (Table 2); the amount of macroaggregates increased with soil layer depth. This is attributable to two factors. First, soil layers with low soil moisture content are not conducive to the formation of macroaggregates (Fan et al. 2010); second, owing to the disturbance of the soil under tillage, organic material could reach the deeper soil layer, resulting in more macroaggregates at that depth. The increase in GMD and MWD (20–40 cm) with the four treatments was ranked in order as follows:  $ST_{35} > ST_{40} > ST_{30} > CT_{25}$ . As the depth of subsoiling increased, not only was the bottom of the plough able to break the soil, but the failure in soil aggregate structure caused by the drastic turning associated with traditional tilling soil was avoided and soil structure was therefore maintained with better stability (Tian et al. 2014).

Soil water content is an important factor for soils that not only provides water for crop growth but also affects nutrient conversion (Nkakini and Akor 2013). The magnitude of the change in soil water content was 24.85–48.67% in 2016 (Figure 5).  $ST_{30}$ ,  $ST_{35}$  and  $ST_{40}$  led to an increase of –3.16, 6.03 and –0.19% at

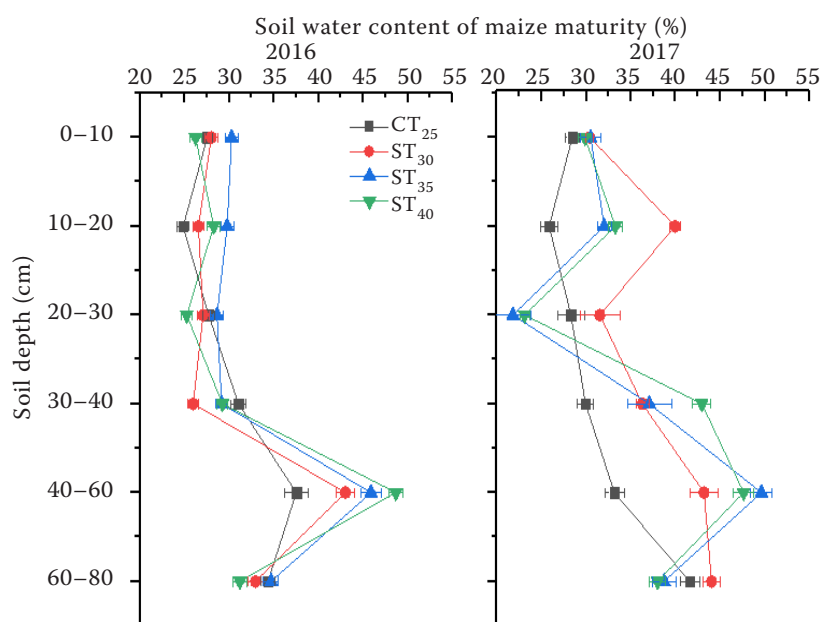


Figure 5. Effects of tillage depth on water content of maize maturity (volumetric water content). Conventional tillage 25 cm ( $CT_{25}$ ); subsoiling 30 cm ( $ST_{30}$ ); subsoiling 35 cm ( $ST_{35}$ ); subsoiling 40 cm ( $ST_{40}$ )

the 0–40 cm soil layer, and 5.73, 12.13 and 11.16% at the 40–80 cm soil layer, respectively, compared to  $CT_{25}$ . The increase in soil water content (30–60 cm) under the four treatments was ranked in order as follows:  $ST_{40} > ST_{35} > ST_{30} > CT_{25}$  in 2017. While soil in the  $CT_{25}$  and  $ST_{30}$  was not broken by the plough bottom, consequently, the bottom of the plough is isolated and the water cannot be infiltrated, causing moisture to flow along the soil surface.  $ST_{35}$  and  $ST_{40}$  adjust the degree of soil compaction to make the soil at the level of 30–40 cm loose and porous, forming a good soil structure (Holthusen et al. 2018). Soil porosity is increased and soil infiltration capacity is enhanced, which increases the field water storage capacity of soil 30–60 cm layer (Evans et al. 1996).

**Summer maize yield.** During the study period, crop yields with the ST were significantly different from those with CT (Table 4). ST significantly increased the number of grains per spike, 1000 grain

weight of maize and the final grain yield increased (Mrabet 2011). At the same time, the results of the present study revealed that, under drought stress, ST could facilitate the uptake of subsoil water and thus increase crop yield, as also reported by Doty et al. (1975). The two-year results revealed that the average yield under the  $ST_{30}$ ,  $ST_{35}$  and  $ST_{40}$  was 3.94, 7.89 and 8.91% higher, respectively, than that under  $CT_{25}$ . These differences in crop yield might be attributed to tillage depth, the effect on the soil granular structure, the depth to which the root of the crop was restricted and variations in the water and nutrient supply to the crop (Lin et al. 2016).

In conclusion, two-year results indicated that ST broke up dense soil layers and improved soil properties in the tilled layer as the depth increased; it is important to apply appropriate tillage practices that avoid the degradation of soil structure and maintain crop yield as well as ecosystem stability. Compared to  $CT_{25}$  and

Table 4. Effect of different tillage depth on yield and its components

Treatment	Ear number ( $10^4$ ear/ha)		Grain number per ear (grain/ear)		1000-grain weight (g)		Yield (t/ha)	
	2016	2017	2016	2017	2016	2017	2016	2017
$CT_{25}$	5.96 <sup>a</sup>	5.67 <sup>b</sup>	475.63 <sup>b</sup>	564.24 <sup>b</sup>	298.37 <sup>c</sup>	302.52 <sup>b</sup>	8.73 <sup>b</sup>	10.02 <sup>b</sup>
$ST_{30}$	6.18 <sup>a</sup>	5.73 <sup>ab</sup>	528.32 <sup>a</sup>	615.49 <sup>a</sup>	304.12 <sup>b</sup>	305.61 <sup>b</sup>	9.16 <sup>a</sup>	10.33 <sup>a</sup>
$ST_{35}$	6.21 <sup>a</sup>	5.81 <sup>a</sup>	556.97 <sup>a</sup>	618.06 <sup>a</sup>	304.89 <sup>b</sup>	304.29 <sup>b</sup>	9.27 <sup>a</sup>	10.96 <sup>a</sup>
$ST_{40}$	6.19 <sup>a</sup>	5.82 <sup>a</sup>	571.18 <sup>a</sup>	624.11 <sup>a</sup>	308.47 <sup>a</sup>	312.17 <sup>a</sup>	9.30 <sup>a</sup>	11.12 <sup>a</sup>

Within each factor, means in the same column followed by the same letters are not significantly different at  $P < 0.05$  (least significance difference (*LSD*) test); conventional tillage 25 cm ( $CT_{25}$ ); subsoiling 30 cm ( $ST_{30}$ ); subsoiling 35 cm ( $ST_{35}$ ); subsoiling 40 cm ( $ST_{40}$ )

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ST<sub>30</sub>, the effect of ST<sub>35</sub> and ST<sub>40</sub> on the construction of reasonable soil layer is more significant, reduced soil bulk density compaction and controlled soil aggregate structure (especially in the 20–40 cm soil layer), the change of soil structure improves the soil water holding capacity of ST<sub>35</sub> and ST<sub>40</sub> in the soil layer of 30–60 cm, with greater maize yield and reduced mechanical power consumption. The subsoiling tillage at 35 cm constituted the optimum tillage depth for Brow loam in the NCP.

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