TILLAGE TIME AFFECTS SOIL HYDRO-THERMAL PROPERTIES, SEEDLING GROWTH AND YIELD OF MAIZE (*ZEA MAYS* L.)

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Abstract. Two-year experiments were conducted to determine optimum tillage time to improve soil compaction and hydro-thermal properties for maize growth. Two tillage treatments: no-tillage (NT), and subsoiling (SS) were performed in correspondence to eight tillage times from March 25 to July 20 (I: March 25, II: April 10, III: April 25, IV: May 10, V: May 25, VI: June 10, VII: July 5, and VIII: July 20) at 15 days interval, synchronously with eight sowing times. SS significantly decreased soil bulk density (0-30 cm) by about 0.13 g cm^{-3} at times of I–V, and about 0.08 g cm^{-3} at VI–VIII. Increment in total soil porosity due to SS was about 3.88% during I–V and about 2.27% at VI–VIII. SS significantly increased soil moisture content by 1.60% in 10-30 cm soil profile. Soil minimum temperature significantly increased by about 0.58 °C (0-20 cm) for I–V, while an increase of 1.06 °C (0-10 cm) was seen for maximum soil temperature due to SS. Greater seedling dry matter coupled with higher growth, and yield improvement was achieved with SS. Dry matter accumulation and grain yield was maximum for May 25 to June 10 sowing as compared to early (22%, 43.5%) and late (60%, 41%, respectively) sowing due to SS versus NT. Initial SS intervals could alleviate soil compaction and low temperature stress for spring maize, with improved soil hydrothermal properties.
Keywords: *subsoiling time, soil bulk density, soil moisture, soil temperature, maize growth*

Introduction

No-tillage in maize (*Zea mays* L.) is the dominant agricultural practice in Huang-Huai-Hai (HHH) maize growing region in China, and the long-term no-tillage is often unfavorable for the growth of maize. Soil compaction has been a major limiting factor for soil environment and plant growth (Zheng and Yan, 2006). To improve soil environment and health, subsoiling tillage as an effective measure is getting popular for maize growth (Ji et al., 2013). Normally, soil tillage and seed sowing are always conducted in June with low precipitation and high temperature in HHH region. Although, no-tillage is practiced for maize sowing in HHH region, except a little soil disturbance at the time of sowing, under winter-wheat and summer-maize cropping system. However, intensive tillage could cause serious soil surface water evaporation during this period, especially with high temperature (Yu and Zhang, 2005), and intensive tillage over longer periods also alters the chemical and physical properties of soil (Lozano-García and Parras-Alcántara, 2014; Jabro et al., 2009). This could lead to a severe drought stress for maize seedling growth (Zhou et al., 2009). Especially under the recent scenario of climate change, in which air temperature is increasing and causing irregular rainfall flashes in northern China (Zafar et al., 2018; Piao et al., 2010; Guo et al., 2010). To avoid the negative effects of soil problems and external micro and macro climate on maize growth and development, the time of soil tillage and sowing date considering the external environment should be given greater attentions (Noor,

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2017; Yin et al., 2017). Therefore, identifying an effective tillage time to decrease soil compaction level and improving soil hydro-thermal properties is very important for the maize seedling growth (Nath and Lal, 2017; Lu et al., 2016).

Recently, great progress has been made through soil tillage management in reducing soil bulk density and increasing soil moisture storage. Subsoiling tillage is reported as conservation tillage practice, by improvement of soil characteristics for maize sowing and seedling growth (Liu et al., 2009; Hou et al., 2012; Hoffmann and Kismányoky, 2001). Many studies indicated that subsoil deep tillage could break the soil plough pan and reduces soil bulk density to a proper soil compaction in northeast China (Wang et al., 2014). Soil structure and hydro-thermal characteristics are not only influenced by soil tillage management, but also highly sensitive to the external environmental conditions such as temperature and precipitation (Karandish and Shahnazari, 2016; Hartmann et al., 2012; Bhaduri et al., 2017).

Therefore, studying the effects of subsoiling tillage implemented at different time intervals has practical guiding value for selecting optimal soil tillage management in maize. Our objectives in present study were, in the process of soil improvement, (1) to find the differential effects of subsoiling tillage on soil compaction and hydro-thermal properties at different subsoiling tillage times; (2) to evaluate the specific subsoiling tillage time alleviating the soil compaction stress at maize seedling growth; (3) to identify optimum time for subsoiling tillage for improving soil compaction problem and minimizing drought stress effects encountered by maize at the seedling stage in HHH region.

Materials and methods

Site description

The field experiments were conducted in Xinxiang Experiment Station of Chinese Academy of Agricultural Sciences, Henan Province, China (35°18áN, 113°54áE). Soil textural class for studied site is classified as clay loam (ISSS Classification, International Soil Science Society), with percentage composition of sand, silt and clay as 32.95, 34.2 and 32.85%, respectively (saturation: 38.5%). Soil bulk density was 1.29 g cm^{-3}, 1.34 g cm^{-3}, 1.55 g cm^{-3} and 1.52 g cm^{-3} at 0-10 cm, 10-20 cm, 20-30 cm and 30-40 cm soil depth, respectively. Major soil nutrient contents analyzed were: organic matter 12.55 g kg^{-1}, total nitrogen 1.13 g kg^{-1}, available phosphorus 16.15 mg kg^{-1}, and 109.95 mg kg^{-1} available potassium (pH = 8.21, EC = 1.2 dSm^{-1}, slope gradient with negligible risk of soil erosion). Usual crop rotation for this area is double cropping system with winter-wheat and summer-maize, in that rotary tillage (15-20 cm) is practiced for wheat and no-tillage farming for maize crop is followed usually.

Annual mean temperature and accumulated precipitation conditions from March to July during 1990 to 2012 are shown in *Figure 1*. From year 1990 to 2012, annual accumulated precipitation had a decline trend, whereas annual mean temperature gradually increased.

Experimental design and soil tillage management

The experiment was conducted from 2011 to 2012. Randomized complete block design was used with split plot arrangement and three replications. Main plots were assigned to tillage times correspondingly with eight sowing intervals starting from

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March 25 to July 20 (I: March 25, II: April 10, III: April 25, IV: May 10, V: May 25, VI: June 10, VII: July 5, and VIII: July 20). Whereas, in subplots two soil tillage treatments just before the maize sowing were conducted viz. SS: subsoiling tillage management involved complete soil inversion and burial of crop residues to a depth of 30 cm using a stripe deep loosening machine (Hehuinong machine Co. Ltd., Beijing, China)., NT: no tillage for two consecutive years. The experimental plots were 30 m long and 3.6 m wide and consisted of 6 rows. Maize sowing and soil tillage were conducted at the same day, so the experiment had eight sowing dates correspondingly. There was no deep soil tillage management for the rotational crops and the plough pan lies at the depth of 20-30 cm of soil profile. The maize variety Zhengdan-958 was planted at the density of 67500 plants ha^{-1} with an 80-40 cm wide/narrow row spacing pattern. N fertilizers at 225 kg N ha^{-1} (Urea: 46% N) were applied in two split applications: 1/3 as basal application before planting, and the remaining 2/3 as side-dressing at the V8-V9 growth stage. Phosphate (P_2O_5) and Potassium (K_2O) fertilizers were applied at 75 kg/ha and 150 kg/ha before sowing, respectively.

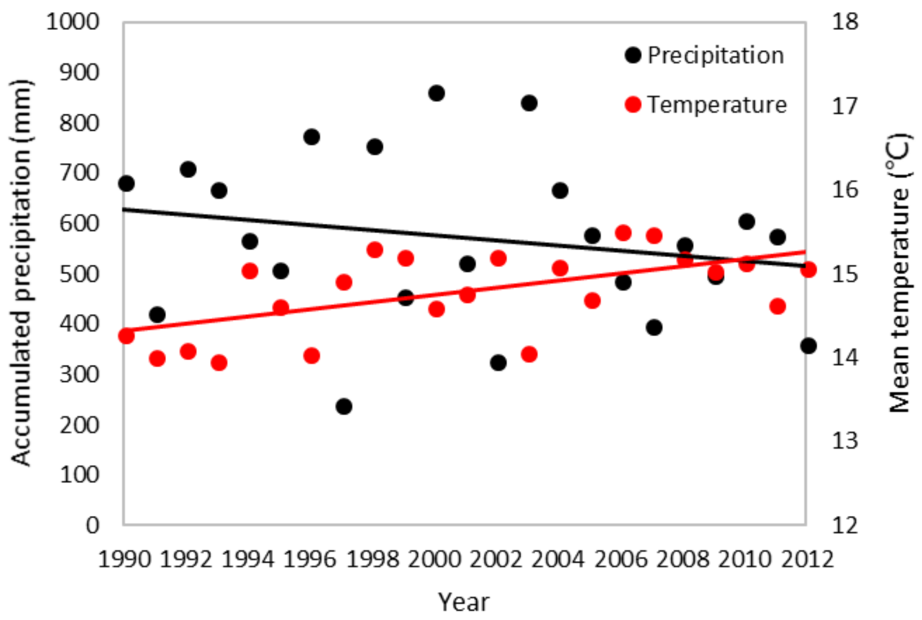

Figure 1. *Changes of annual mean temperature and accumulated precipitation from 1990 to 2012*

Sampling and measurement

Soil samples were collected from four soil depths (0-10 cm, 10-20 cm, 20-30 cm, and 30-40 cm) for each tillage treatment 20 days after soil tillage implementation. In each plot, soil sample was obtained to determine soil bulk density, soil porosity, soil moisture content and soil temperature. For plant samples plant shoots were cut manually at the ground level to determine the shoot dry weight, and plant roots were dug out from soil profile of 40 cm depth to determine the root dry weight for 3 plants per plot at 20 days after soil tillage management.

Soil bulk density was determined by weighing method (*Eq. 1*) with cutting-ring which had a fixed volume of 100 cm^3 to sample the soil maintaining the soil physical structure at the same time. Then weighing the soil fresh weight and dry weight:

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$$\text{Soil bulk density (g/cm}^3\text{)} = \frac{\text{soil dry weight (g)}}{\text{cutting-ring volume (cm}^3\text{)}} \quad \text{(Eq.1)}$$

The measurement was made at four depths of soil (0-10, 10-20, 20-30, and 30-40 cm) at seedling stage of maize. The measurement was repeated three times in each plot. Total soil porosity was calculated (*Eq. 2*) from soil bulk density as follows:

$$\text{Total soil porosity (100\%)} = \frac{\text{(soil density} - \text{soil bulk density)}}{\text{soil density}} \quad \text{(Eq.2)}$$

where soil density is 2.65 g cm^{-3}. For soil moisture content (*Eq. 3*), soil samples were taken from the 0-40 cm soil profile at 10 cm intervals and oven-dried to constant weight in an aluminum container.

$$\text{Soil moisture content (100\%)} = \frac{\text{(fresh soil weight} - \text{dry soil weight)}}{\text{dry soil weight}} \quad \text{(Eq.3)}$$

The measurement was repeated three times in each plot at 20 days after sowing of maize. For soil temperature measurement, thermistor temperature probes were buried at three points in each plot and four depths in the 0-20 cm soil profile (0-5, 5-10, 10-15, and 15-20 cm). Daily soil minimum and maximum temperatures were measured at consecutive 20 days after sowing of maize.

Sampling was done from each plot by cutting three adjacent plants in a row at ground level to determine leaf area and dry matter accumulation at V3, V6, VT and R3 growth stages. Leaf area index (LAI) was calculated by multiplying leaf area with plant density per m^2. Already sampled three plants were oven dried at 105 °C for one hour initially and then at 71 ± 1 °C to measure dry matter accumulation. Twenty days after sowing of maize, five whole plants were randomly sampled from each sub-plot and then plant shoot and roots were separated and dry matter was determined. At harvest stage, maize ears were hand harvested in the two central rows (the length of each row was 20 m) of each plot, dried and shelled. Dry matter and yields were obtained according to standard procedures. The maize yield potential (YP) in HHH area was obtained by the Hybrid-Maize simulation model (Yang et al., 2004).

The effect of soil tillage time on all analyzed parameters was tested using a one-way analysis of variance (ANOVA) (SPSS 13.0 for Windows; SPSS Inc., Chicago, USA). Tukey's HSD method was used as post hoc test for multiple comparisons of means. Mean data was presented for both years (2011 and 2012) for all the studied parameters except for some growth attributes (LAI, dry matter accumulation), due to non-significant year effect for the studied period.

Results

Soil and external environment before soil tillage

The values of soil temperature and soil moisture were significantly lower at initial soil tillage time intervals than later tillage intervals (*Table 1*). Soil mean temperature at different soil tillage times were recorded as the sequence of I<II<III<IV<V<VI<VII<VIII.

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Table 1. *Soil hydrothermal properties before soil tillage in 0-40 cm soil depth*

Soil tillage time	I	II	III	IV	V	VI	VII	VIII
Soil mean temperature (°C)	16.53	17.23	18.52	22.39	24.60	25.63	29.53	30.00
Soil mean moisture content (%)	14.14	14.47	15.15	15.84	16.56	16.66	15.87	17.14
Soil mean bulk density ($g\ cm^{-3}$)	1.36	1.35	1.36	1.32	1.39	1.31	1.37	1.37

I: March 25, II: April 10, III: April 25, IV: May 10, V: May 25, VI: June 10, VII: July 5, VIII: July 20

The values of soil mean moisture content at different soil tillage times were recorded in the sequence of I<II<III<IV<VII<V<VI<VIII. The values of effective accumulated temperature for different soil tillage times were as the sequence of IV>III>V>II>VI>VII>I>VIII during whole crop growth period (*Fig. 2*).

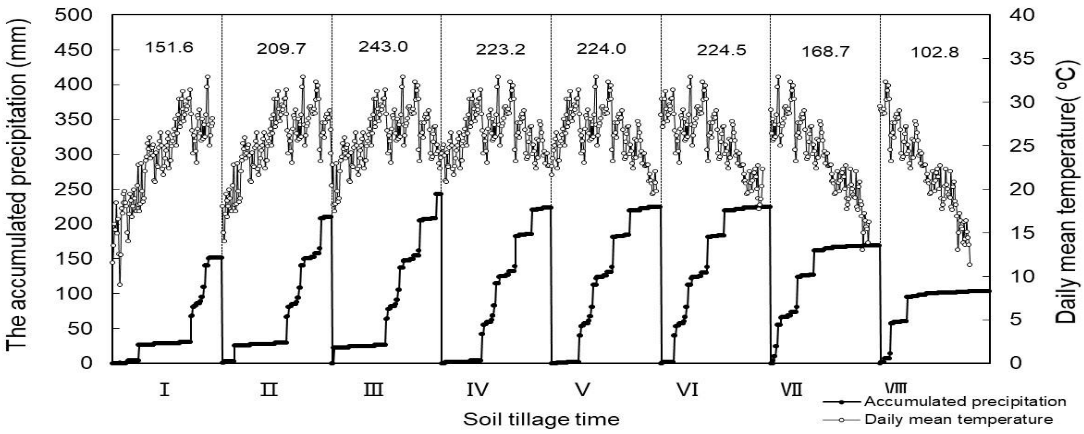

Figure 2. *Effective accumulated temperature (top word in figure), daily mean temperature (center line in figure) and accumulated precipitation (bottom line in figure) during growth cycle of maize at different soil tillage time. I: March 25, II: April 10, III: April 25, IV: May 10, V: May 25, VI: June 10, VII: July 5, and VIII: July 20*

Soil bulk density

In 0-10 cm soil layer, SS significantly decreased soil bulk density by about 0.13 g cm^{-3} ($P < 0.01$) at former tillage time of I–V, and the decrease was about 0.04 g cm^{-3} ($P < 0.05$) at later soil tillage intervals of VI–VIII, compared to NT (*Fig. 3*). In 10-20 cm soil layer, soil bulk density significantly decreased by about 0.07 g cm^{-3} ($P < 0.05$) at each soil tillage time under SS treatment compared to NT. Because of the destruction of soil hard plough pan, SS significantly decreased soil bulk density by about 0.15 g cm^{-3} ($P < 0.01$) at each soil tillage time compared to NT in 20-30 cm soil layer.

Soil porosity

Because of the decrease in soil bulk density, soil total porosity was therefore increased significantly (*Fig. 4*). In 0-10 cm soil layer, SS significantly increased soil total porosity by 4.18% ($P < 0.01$) at initial tillage intervals of I–V, and the increment was 2.38% ($P < 0.05$) at later soil tillage time of VI–VIII compared to NT. SS significantly increased soil porosity with average of 3.75% ($P < 0.01$) in top (0-30 cm) soil layer at initial tillage intervals of I–V, while the increment was 2.26% ($P < 0.05$) at tillage intervals VI–VIII, as compared to NT.

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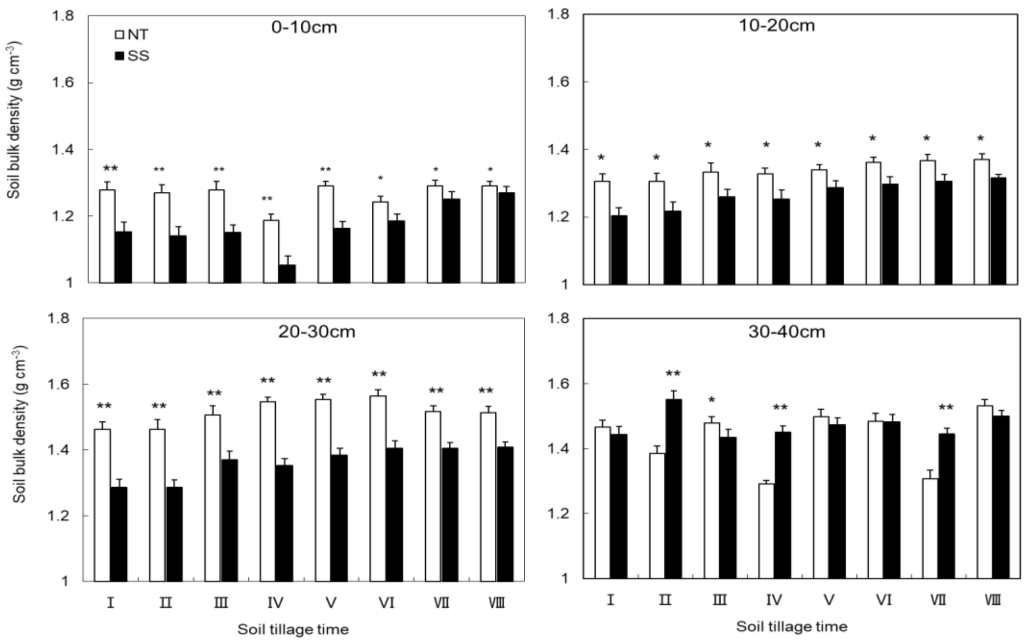

Figure 3. *Soil bulk density in 0–40 cm depth at different soil tillage time. NT: no tillage, SS: subsoiling tillage; I: March 25, II: April 10, III: April 25, IV: May 10, V: May 25, VI: June 10, VII: July 5, and VIII: July 20; ** above the column indicate statistical significance at the P = 0.01 level within the same soil tillage time; * above the column indicate statistical significance at the P = 0.05 level within the same soil tillage time*

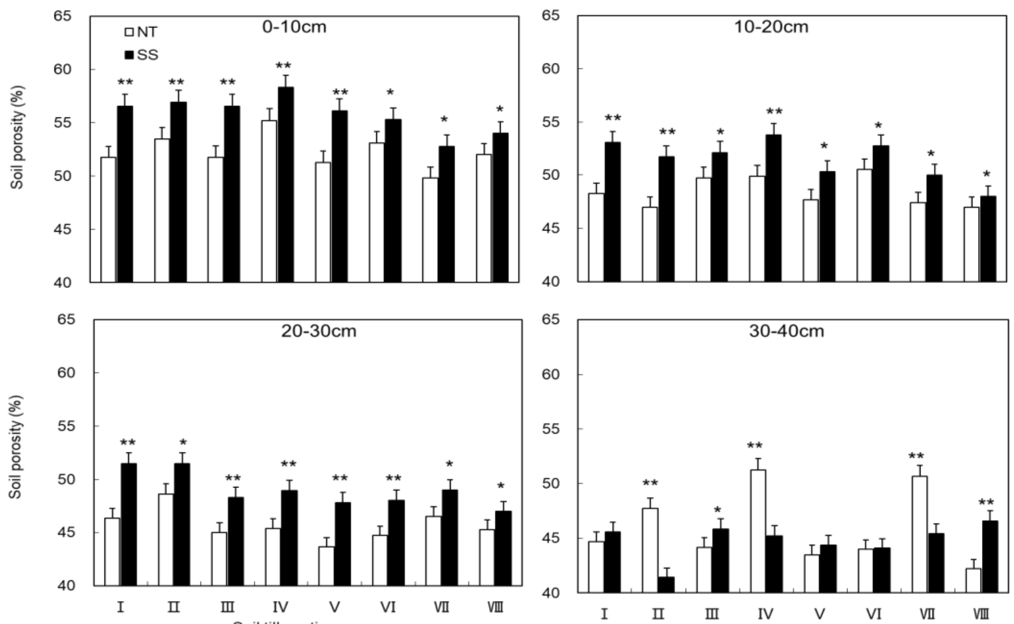

Figure 4. *Soil porosity in 0-40 cm depth at different soil tillage times. NT: no tillage, SS: subsoiling tillage; I: March 25, II: April 10, III: April 25, IV: May 10, V: May 25, VI: June 10, VII: July 5, and VIII: July 20; ** above the column indicate statistical significance at the P = 0.01 level within the same soil tillage time; * above the column indicate statistical significance at the P = 0.05 level within the same soil tillage time*

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Soil moisture content

In 0-10 cm soil layer, SS significantly decreased soil moisture content by 2.06% ($P < 0.01$) at later soil tillage time of VI–VIII, because of the soil disturbance coincidence with high soil evaporation (*Fig. 5*). In 10-20 cm soil layer, SS significantly increased soil moisture content by 2.24% ($P < 0.01$) at intervals I, II, III, V, and the increment was 1.13% ($P < 0.05$) at later intervals of IV, VI, VII, VIII. In 20-30 cm soil layer, soil moisture content significantly increased by 2.26% ($P < 0.01$) at I, II, V, VI intervals, and the increment was about 1.13% ($P < 0.05$) at later intervals of III, IV, VII, VIII.

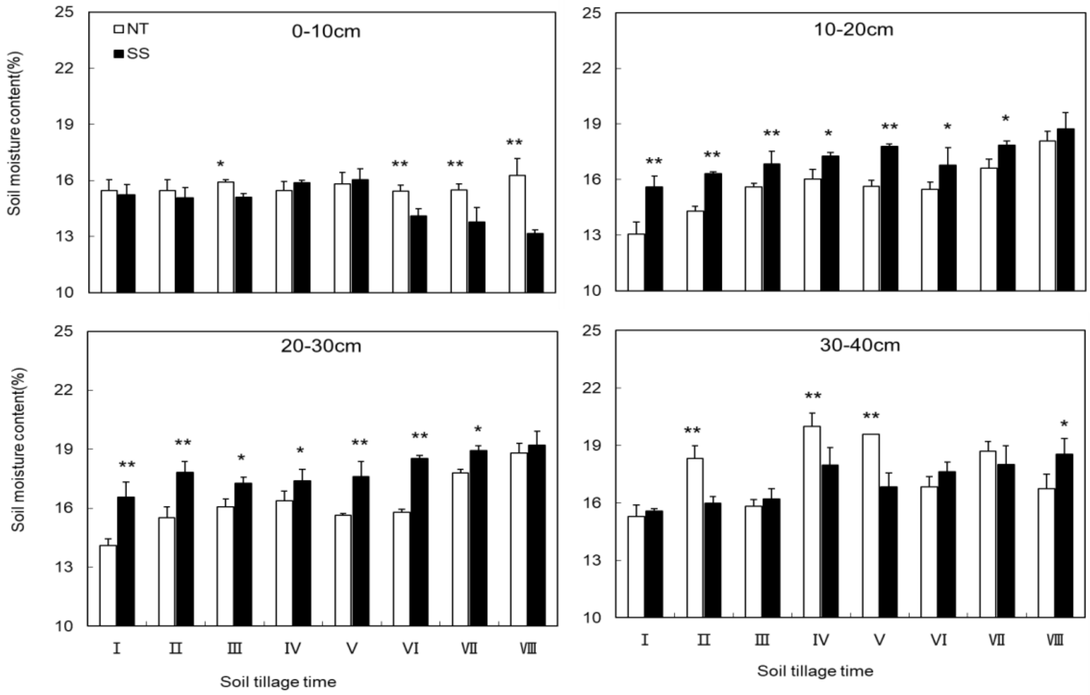

Figure 5. *Soil moisture content in 0–40 cm depth at different soil tillage. NT: no tillage, SS: subsoiling tillage; I: March 25, II: April 10, III: April 25, IV: May 10, V: May 25, VI: June 10, VII: July 5, and VIII: July 20; ** above the column indicate statistical significance at the P = 0.01 level within the same soil tillage time; * above the column indicate statistical significance at the P = 0.05 level within the same soil tillage time*

Soil temperature

In 0-10 cm soil layer, SS was able to increase soil minimum, maximum and mean temperatures as compared to NT (*Table 2*). For soil lowest temperature, the significant increment was 1.29 °C ($P < 0.05$) at tillage time of I, II, while it was 0.51 °C at intervals III, IV, V, VI. For soil maximum temperature, the increment was about 1.06 °C ($P < 0.05$) at each soil tillage time. For soil mean temperature, the increment recorded was 1.12 °C ($P < 0.05$) at former soil tillage intervals of I, II, while it was 0.65 °C at intervals III, IV, V, VI, VII, VIII. In 10-20 cm soil layer, SS just increased soil lowest temperature compared to NT, the increment was 0.43 °C for tillage intervals of I–V, while it was -0.28 °C at later soil tillage time of VI–VIII, as compared to NT.

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Table 2. *Soil minimum, maximum and mean temperature in 0–20 cm soil depth at 20 days after sowing of maize*

Soil depth (cm)	Soil temperature (°C)	Soil tillage method	Soil tillage time							
			I	II	III	IV	V	VI	VII	VIII
0–5	Minimum	NT	14.71b	15.48b	18.80b	21.10a	22.00a	25.24a	27.00a	26.75a
		SS	15.95a	16.62a	19.65a	21.65a	22.50a	25.86a	26.47a	25.75b
	Maximum	NT	22.52b	24.71b	29.15b	30.95b	30.95a	36.69a	35.95b	33.00b
		SS	23.43a	25.62a	29.95a	32.10a	31.70a	37.24a	37.69a	34.00a
	Mean	NT	18.62b	20.06b	23.98b	26.00b	26.45a	30.97a	31.47a	29.88a
		SS	19.69a	21.11a	24.80a	26.88a	27.10a	31.55a	32.08a	29.88a
5–10	Minimum	NT	11.76b	14.66b	18.65b	21.50a	22.40a	25.62a	26.84a	26.65a
		SS	13.33a	15.78a	19.35a	22.00a	22.65a	25.76a	26.32a	25.90a
	Maximum	NT	19.19b	21.09b	26.65a	27.60b	29.15b	34.24a	33.95b	31.75b
		SS	22.14a	21.91a	27.05a	29.40a	30.10a	34.71a	35.42a	33.00a
	Mean	NT	15.48b	17.86b	22.33b	24.55b	25.78a	29.93a	30.40a	29.20a
		SS	16.87a	18.84a	23.20a	25.70a	26.38a	30.24a	30.87a	29.45a
10–15	Minimum	NT	15.33a	16.26a	19.50a	22.00a	22.80a	26.09a	26.74a	27.18a
		SS	15.95a	16.75a	20.20a	22.35a	23.20a	25.81a	26.05a	26.55a
	Maximum	NT	21.59a	22.10a	24.65a	26.90a	27.95a	31.19a	32.16a	30.90a
		SS	20.67b	21.19b	24.25a	26.05a	28.45a	31.14a	30.68b	30.20a
	Mean	NT	18.46a	19.13a	22.43a	24.45a	25.38a	28.64a	29.17a	29.04a
		SS	18.31a	18.97a	21.90a	24.20a	25.83a	28.48a	28.49a	28.35a
15–20	Minimum	NT	15.66a	16.29a	19.26a	22.50a	23.35a	27.14a	27.16a	27.05a
		SS	16.10a	16.71a	19.65a	23.00a	23.65a	27.00a	26.79a	27.55a
	Maximum	NT	18.95a	19.18a	23.25a	26.05a	26.35a	30.05a	30.11a	29.85a
		SS	18.00b	18.62a	22.75a	25.15b	25.95a	30.00a	30.79a	29.30a
	Mean	NT	17.10a	17.73a	21.26a	24.28a	24.85a	28.60a	28.63a	28.45a
		SS	17.05a	17.67a	21.20a	24.08a	24.80a	28.52a	28.79a	28.43a

NT: no tillage, SS: subsoiling tillage; I: March 25, II: April 10, III: April 25, IV: May 10, V: May 25, VI: June 10, VII: July 5, and VIII: July 20. Values between NT and SS for each tillage date followed by different letters are significantly different at $P < 0.05$

Relationship of soil temperature and soil moisture content

Soil moisture content influences the range of soil temperature under different tillage treatments. For the soil lowest temperature, it showed increasing trend with the soil moisture content increasing at tillage time of I, II, III, IV, and V when the soil temperature was low (*Fig. 6*). For soil maximum temperature and daily mean temperature, it showed decreased tendency with the soil moisture content increasing at tillage time of IV, V, VI, VII, and VIII. Hence, the soil lowest temperature was easily affected by soil moisture when the soil temperature was very low.

Growth

Among tillage treatments, SS performed better in improving LAI over the all soil tillage intervals as compared to NT, for both the years (*Table 3*). During 2012 year, an increasing trend for LAI was recorded for the intervals I–V, whilst a decrease was

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observed after that for the intervals VI–VIII. This decreasing trend is significantly visible for both the years during VT and R3 growth stages, because of delayed sowing time as compared to initial sowing intervals of I–V.

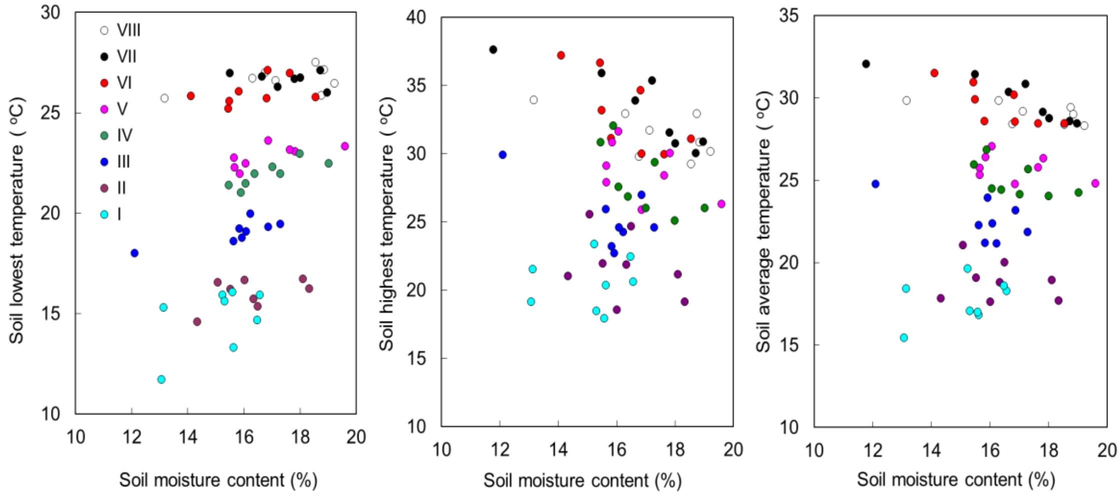

Figure 6. *Relationship of soil temperature and soil moisture content at different soil tillage time. I: March 25, II: April 10, III: April 25, IV: May 10, V: May 25, VI: June 10, VII: July 5, and VIII: July 20*

Table 3. *LAI of maize during crop growth period of maize at eight soil tillage times*

Year	Growth stage	Soil tillage	Soil tillage time							
			I	II	III	IV	V	VI	VII	VIII
2011	V3	NT	0.05b	0.06b	0.06b	0.07b	0.07b	0.08b	0.10b	0.11b
		SS	0.06a	0.07a	0.07a	0.08a	0.09a	0.09a	0.11a	0.12a
	V6	NT	0.43a	0.46b	0.49b	0.58b	0.64b	0.65a	0.65b	0.75b
		SS	0.43a	0.48a	0.51a	0.61a	0.65a	0.65a	0.67a	0.77a
	VT	NT	4.14b	4.33b	4.50b	4.58b	4.91b	4.77b	3.49b	3.74b
		SS	4.41a	4.69a	4.79a	4.84a	5.16a	5.07a	3.74a	4.03a
	R3	NT	3.14b	3.14b	3.68b	3.88b	4.46b	4.49b	3.82b	3.61b
		SS	3.37a	3.37a	3.82a	4.06a	4.59a	4.57a	3.95a	3.72a
2012	V3	NT	0.05b	0.06b	0.06b	0.07b	0.07b	0.08b	0.10b	0.11b
		SS	0.06a	0.07a	0.07a	0.08a	0.09a	0.09a	0.11a	0.12a
	V6	NT	0.38b	0.47b	0.58b	0.55b	0.63b	0.42b	0.45b	0.41b
		SS	0.43a	0.52a	0.63a	0.57a	0.67a	0.46a	0.50a	0.44a
	VT	NT	4.41a	4.92a	4.29b	3.68b	4.56b	4.35b	4.20a	3.09b
		SS	4.27b	4.71b	4.36a	3.85a	4.97a	4.69a	4.05b	3.33a
	R3	NT	3.91a	4.02b	3.89b	3.69a	4.15b	4.23a	3.52b	2.99a
		SS	3.90a	3.98a	3.96a	3.42b	4.51a	4.13b	3.92a	3.00a

NT: no tillage, SS: subsoiling tillage; I: March 25, II: April 10, III: April 25, IV: May 10, V: May 25, VI: June 10, VII: July 5, and VIII: July 20; Values between NT and SS for each tillage date followed by different letters are significantly different at $P < 0.05$

From *Figure 7*, we could see that SS caused a significant increase in dry weight of shoot and root at 20 days after sowing of maize. For shoot dry weight, the highest value was obtained at soil tillage time of VIII, while the highest increment was obtained at soil tillage time of I under SS (*Fig. 7*). SS significantly increased shoot dry weight by 13.85% ($P < 0.01$) at initial tillage intervals of I–IV, and by 7.83% ($P < 0.05$) at later soil tillage time of V– VIII compared to NT. For root dry weight, the highest value was obtained at soil tillage time of VI, while the highest increment was obtained at soil tillage time of I under SS. Similar to LAI, dry matter accumulation varied across different sowing intervals as well as sampling stages of crop growth period (V3–R3) (*Table 4*). Maximum value for dry matter was found for SS during sowing interval VI (2011) and V (2012) at R3 sampling stage.

Table 4. *Dry matter accumulation of maize during crop growth stages of maize for eight soil tillage times*

Year	Growth stage	Soil tillage	Soil tillage time							
			I	II	III	IV	V	VI	VII	VIII
2011	V3	NT	0.34b	0.47b	0.61b	0.66b	0.91b	1.16b	1.48b	1.64b
		SS	0.39a	0.53a	0.69a	0.75a	0.98a	1.25a	1.60a	1.75a
	V6	NT	6.43b	6.87b	6.40a	8.20a	8.45b	10.47b	11.08b	12.90a
		SS	8.13a	9.10a	6.97a	8.83a	9.62a	11.03a	12.49a	12.97a
	VT	NT	90.03b	100.80b	116.67b	116.80b	134.53a	129.81b	121.87b	116.85b
		SS	103.20a	113.40a	133.10a	132.99a	137.67a	139.40a	137.57a	132.99a
	R3	NT	177.37b	171.60b	186.40b	210.23b	214.22b	238.47b	186.40b	136.65b
		SS	186.67a	186.03a	198.60a	227.07a	228.45a	252.73a	198.60a	153.70a
2012	V3	NT	0.34b	0.45b	0.55b	0.58b	0.98b	1.07b	1.42b	1.75a
		SS	0.41a	0.51a	0.66a	0.67a	1.07a	1.18a	1.53a	1.79a
	V6	NT	4.10b	4.53b	5.47a	5.23a	6.36b	6.60b	8.42a	8.75a
		SS	5.17a	5.25a	5.67a	5.67a	7.35a	8.30a	8.53a	9.31a
	VT	NT	98.53b	98.53b	98.13b	102.53b	110.63b	120.10a	94.23b	86.00a
		SS	105.97a	102.00a	107.97a	108.17a	115.20a	120.83a	105.30a	86.20a
	R3	NT	194.53b	192.53b	193.97b	198.10b	214.42b	201.10b	170.20b	145.37a
		SS	198.77a	194.87a	196.80a	203.27a	219.82a	204.97a	176.63a	146.13a

NT: no tillage, SS: subsoiling tillage; I: March 25, II: April 10, III: April 25, IV: May 10, V: May 25, VI: June 10, VII: July 5, and VIII: July 20; Values between NT and SS for each tillage date followed by different letters are significantly different at $P < 0.05$

Regardless of soil tillage time, the grain yield of maize was significantly higher under the SS management than no-tillage treatment (*Fig. 8*). In terms of tillage intervals, the yield of maize was highest in the SS tillage management implemented at VI, but the highest increment of yield was recorded at SS tillage implemented at I. The highest yield potential (YP) of maize was recorded at soil tillage time of V. The potential equivalent was in the range of 71.89–85.10% at SS, while it was 67.08-81.78% (range) at NT for tillage times I, II, III, IV, V, VI, and VII, respectively.

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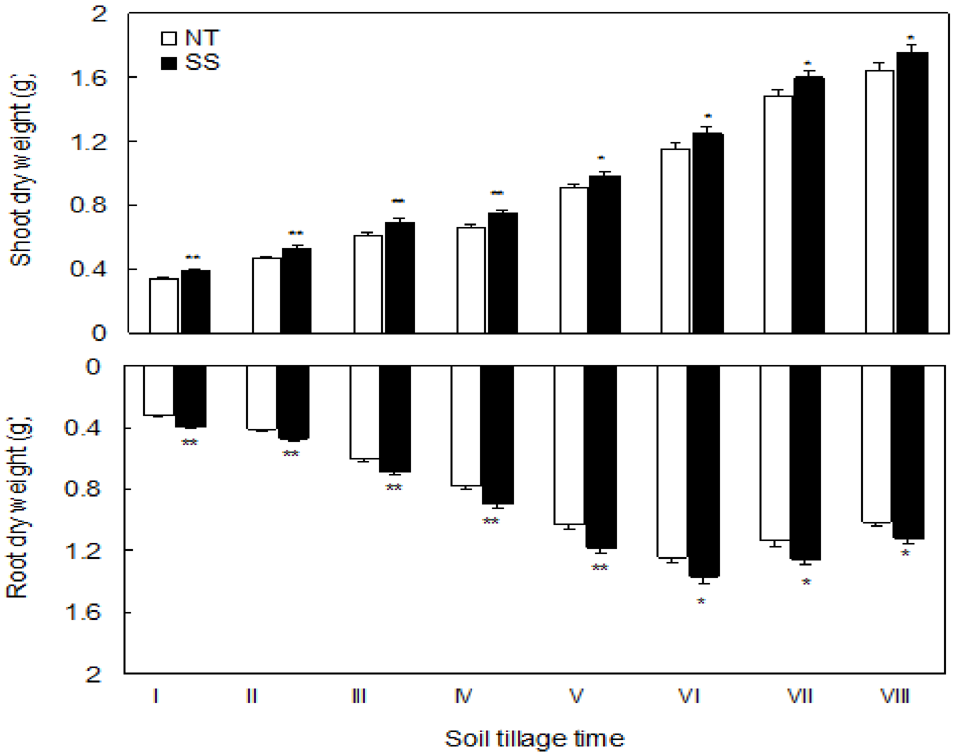

***Figure 7.** Shoot and root dry matter at 20 days after sowing of maize. NT: no tillage, SS: subsoiling tillage; I: March 25, II: April 10, III: April 25, IV: May 10, V: May 25, VI: June 10, VII: July 5, and VIII: July 20; ** above the column indicate statistical significance at the P = 0.01 level within the same soil tillage time; * above the column indicate statistical significance at the P = 0.05 level within the same soil tillage time*

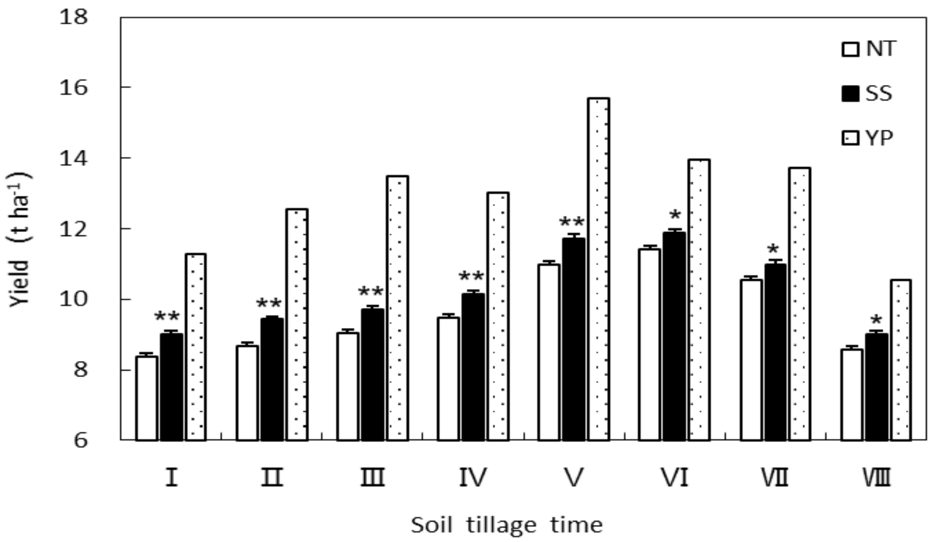

***Figure 8.** Final grain yield of maize at different soil tillage time. NT: no tillage, SS: subsoiling tillage, YP: yield potential; I: March 25, II: April 10, III: April 25, IV: May 10, V: May 25, VI: June 10, VII: July 5, and VIII: July 20; ** above the column indicate statistical significance at the P = 0.01 level within the same soil tillage time; * above the column indicate statistical significance at the P = 0.05 level within the same soil tillage time*

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Discussion

Soil bulk density is an important indicator for soil stiffness (Carter, 1990). Liang et al. (2010) and Liu et al. (2010) found that subsoiling tillage could break the soil hard plough pan and loosen the compacted soil, thereby reducing soil bulk density. Meanwhile because of the dryness and reduced soil viscosity with low soil moisture and temperature, the soil structure could easily be altered (Yang et al., 2013). Our results indicated that SS significantly reduced soil bulk density in 0-30 cm soil layer, especially at the former soil tillage time of I–V, when compared to no-tillage treatment (*Fig. 3*). These results are in disagreement with that of Gürsoy et al. (2011). Whereas, Ozpinar and Ozpinar (2015) found a significant decrease in soil bulk density, confirming our results, in top soil due to tillage practices in a five-year experiment at enhancing maize productivity. In 20-30 cm soil layer, because of the destruction of hard plough layer, soil bulk density showed a much significant decrease in present case, promising for sustainable field maize production in China.

Assouline (2006) suggested that, soil can be significantly loosened and the proportion of large pores can be increased significantly under SS tillage. The level of soil porosity is related to intensity of soil tillage (Chen et al., 2009). In present study, the implementation of SS tillage significantly increased soil total porosity in 0-30 cm soil depth compared with no-tillage treatment (*Fig. 4*). This improvement can be attributed to the reason that the level and distribution of soil total porosity were significantly affected by the soil bulk density (Raczkowski et al., 2012; Wang et al., 2017).

Soil moisture content is a basic characteristic required for optimum crop growth. Appropriate soil moisture contents could support uptake of crop root and can regulate the dynamics of soil temperature and heat (Karandish and Shahnazari, 2016; Tsironi and Taoukis, 2017). Assouline (2006) showed that SS could improve soil moisture infiltration and storage attributed to the decrease in soil bulk density and increased soil total porosity. Meanwhile the SS tillage could break the continuity of soil pores to prevent the evaporation and reduction of deep soil moisture (Osunbitan, 2005), thereby significantly increasing deep-layer soil moisture contents. However, the SS tillage involves excessive soil ploughing, resulting in relatively higher surface soil moisture evaporation due to more exposure to sunshine (Debaeke and Aboudrare, 2004). And the high soil and air temperature accelerate the surface soil moisture evaporation (Wang et al., 2007). Our study showed the same results that SS significantly increased soil moisture content in 10-30 cm soil depth, while the soil moisture content decreased in 0-10 cm soil depth compared with no-tillage (*Fig. 5*). In 10-20 cm soil depth, soil moisture content showed a much significant increase at soil tillage intervals of I, II, III, V, and VI because of the relevant decrease in soil bulk density and increase in soil total porosity due to SS, compared to NT.

In field, seed germination and seedling growth of maize are closely related to soil temperature (Ahmad et al., 2016; Lopushinsky and Max, 1990). Fu et al. (2005) suggested that SS tillage could balance and improve the status of soil temperature through the function of heat preservation on minimum soil temperature conditions and may cause decrease in maximum soil temperature and it could keep the stability of soil temperature, beneficial for the crop growth. In this study, SS tillage increased soil minimum temperature in 0-20 cm soil depth at soil tillage time of I–VI. For soil maximum temperature and daily mean temperature, the increments were only occurred in 0-10 cm soil depth at each tillage time (*Table 2*). Soil temperature jointly determined

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with atmospheric temperature and soil heat conditions are reported to be regulated by soil moisture content and soil porosity (Lakshmi, 2003). Higher soil porosity and moisture content could contribute to heat transfer and storage (Zhang et al., 2009; Wu et al., 2017). For these reasons, the soil minimum temperature showed an increased tendency with increase in soil moisture content, especially at intervals III, IV and V. While the soil maximum and daily mean temperature showed an decreased tendency with increasing soil moisture at later soil tillage time of V, VI, VII and VIII (*Fig. 6*).

Anand et al. (2012) reported that the decrease in soil penetration resistance, increase in soil moisture and temperature could improve the seedling emergence and growth during early spring under low temperature conditions. Tolon-Becerra et al. (2011) showed that better seedling emergence and growth were achieved under soil with lower compaction, and the relationship between root dry matter and maize yields was strongly positive. In our study, SS significantly increased shoot and root dry matter of maize seedling. Though the highest maize seedling dry matter was obtained at SS tillage time of VI, VII and VIII, which are contrary to the findings of Ge et al. (2013). The reason can be described by effective accumulated temperature, daily mean temperature and accumulated precipitation at respective growth stage of maize (*Fig. 2*), the maximum increase in maize seedling matter was obtained at tillage intervals of I, II, III, IV and V (*Fig. 7*). The decrease during former tillage intervals plausibly because of the soil high compaction and low temperature, which may be attributed as main limits for maize seedling growth at March, April, and May (*Fig. 1*). The improvement in soil compaction and temperature significantly enhanced the maize seedling growth, corroborating the findings of Hoffmann and Kismányoky (2001). The increase in maize yield was significantly improved at SS tillage compared with no-tillage management, which is against the results reported earlier by Mohammadi et al. (2013), and SS also decreased the yield gap between yield and yield potential in our case. Though the highest maize yield was harvested at SS tillage time of V, VI and VII, whilst the highest increment in maize yield was harvested at subsoiling tillage time of I, II, III and IV (*Fig. 8*), which are contrary to the results of Zhang et al. (2009). Recently, Moinoddini et al. (2017) also found significant positive effects of deep tillage on maize grain yields as compared to no-tillage during the evaluation of different tillage practices and N application rates under corn-based rotation system. In present case, SS tillage significantly increased soil moisture storage and soil temperature, and improved seedling growth of maize at subsoiling tillage time of I, II, III and IV, as compared no tillage.

Our results indicate that in no-tillage maize growing areas of HHH, soil hydro-thermal properties can be improved by implementing the SS in the month of May and June. This improvement reflects in terms of increased soil temperature, moisture content, porosity and the significant decrease in soil bulk density, which in turn is attributed to better seedling growth and early stand establishment with higher shoot/root parameters, and the succeeding plant growth and final dry matter accumulation. The reason can be explained through the maximum accumulated temperature, precipitation (*Fig. 2*) and the sunshine hours during these months (May, June), which were favorable to improve soil environment and the plant growth under SS tillage implementation, as compared to no-tillage.

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Conclusion

In Huang-Huai-Hai area of China, SS tillage proved effective in improving soil physical and hydro-thermal properties, and improving maize seedling growth and grain yield, especially when implemented at early time (March, April and May). Compared with no-tillage, subsoiling tillage significantly decreased soil bulk density, and greatly increased soil porosity. SS tillage at early time (especially for May and June) significantly increased the soil moisture storage in 10-30 cm soil depth. Soil minimum temperature (0-20 cm) and soil maximum temperature (0-10 cm) significantly increased at SS tillage time of March, April and May. The SS tillage produced maximum dry seedling matter in maize and grain yields compared to no-tillage management, especially when implemented at early time. Because at early sowing of maize, low soil temperature and Spring seasonal drought cause serious hindrance for early stand establishment in HHH. We can conclude that SS tillage could alleviate the soil high compaction and low temperature stress for spring maize, and can alleviate the soil high compaction stress for summer maize. Dry matter accumulation and grain yield was maximum for sowing from May 25 to June 10. It will be of great significance in improving soil environment, seedling growth and grain yield of maize at early sowing with low precipitation and temperature.

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