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Effects of different tillage practices after short-term no-tillage with straw mulching on soil physical properties in Mollisols region of Northeast China

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KEYWORDS

Mollisols protection, no-tillage with straw mulching, soil physical properties, tillage practice

HIGHLIGHTS

- Different tillage practices after short-term no-tillage with straw mulching (NTSM) significantly influenced soil structure and moisture retention in Mollisols in northeastern China.
- Deep plowing enhanced water infiltration and reduced soil bulk density and penetration resistance.
- Subsoil tillage improved subsoil warming and regulated thermal conditions.
- Deep plowing is considered to be a more effective tillage practice after 2-year NTSM for improving soil physical properties.

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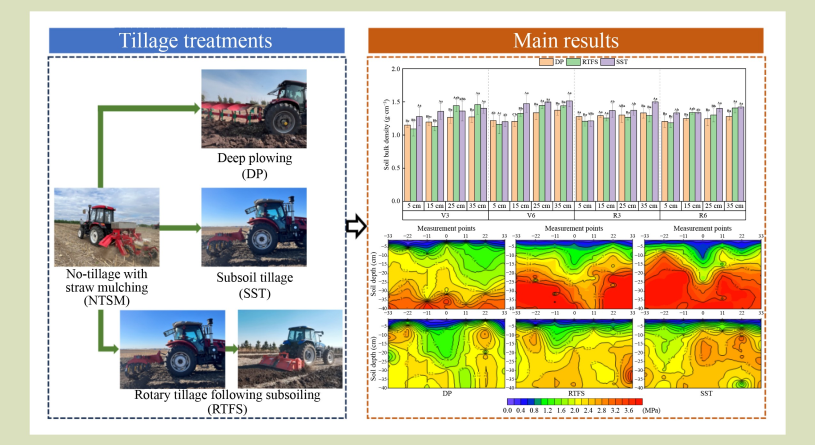
GRAPHICAL ABSTRACT



ABSTRACT

No-tillage with straw mulching (NTSM) is one of the effective conservation tillage practices in China. However, continuous NTSM practice can lead to soil compaction. Therefore, it is of great significance to explore the effects of different tillage practices following short-term NTSM on soil physical properties, which is important for optimizing tillage practices, developing rotational tillage systems and improving soil health. An experiment was conducted with a randomized block design with three replicates of three tillage treatments, viz. deep plowing (DP), rotary tillage following subsoiling (RTFS) and subsoil tillage (SST), following two consecutive years of NTSM from 2019 to 2022 in typical Mollisols of northeastern China. Soil water content (SWC), bulk density (SBD), temperature, penetration resistance (SPR), physical properties, were tested in the 5-, 15-, 25- and 35-cm soil layers in the plant row of each experiment plot at the three-leaf (V3, 21 May), six-leaf (V6, 27 June), milk ripe (R3, 2 August) and full ripe (R6, 20 September) stages of the maize growth cycle in 2022. The results indicated that SWC in the 25- and

35-cm soil layers was significantly higher than in the 5- and 15-cm soil layer under DP treatment at all growth stages ($P < 0.05$). SBD under DP treatment was on average 5.9% and 9.3% lower than under RTFS and SST treatments in 25–35 soil layers (except for the R3 stage) ($P < 0.05$). SPR under DP treatment was on average 18.6% and 33.8% lower than under RTFS and SST treatments in the 15- and 25-cm soil layers ($P < 0.05$). DP treatment was the effective tillage practice after 2 years of NTSM operation for improving soil physical properties.

1 Introduction

The Mollisols region in northeastern China is one of the country's most important grain-producing areas, supporting large-scale maize and soybean production. However, this region faces serious challenges of soil degradation, erosion and fertility decline caused by long-term intensive tillage practices[1,2]. To mitigate these problems, conservation tillage, particularly no-tillage with straw mulching (NTSM), has been widely promoted in the Mollisols region of northeastern China due to its short-term benefits in improving soil structure, increasing organic matter, and reducing erosion[3,4]. Despite these advantages, continuous NTSM may also lead to soil compaction and reduced water infiltration, thereby limiting its long-term sustainability[5]. Consequently, mechanical tillage is often periodically incorporated into farming systems to alleviate compaction and restore soil functionality[6].

Mechanical tillage practices strongly influence soil physical properties, such as soil water content (SWC), bulk density (SBD), temperature (ST) and penetration resistance (SPR), although their effects vary considerably across soil types, climatic conditions and management systems[7,8]. For example, Jabro et al.[9] reported that no-tillage, rotary tillage, and deep plowing did not significantly affect SWC in North Dakota, USA, and studies[10] in northeastern China showed that no-tillage with straw return significantly increased SWC in the 0-10 cm soil layer compared to standard tillage. Also, in the Huanghuaihai Plain of China, combining rotary tillage with 35-40 cm subsoiling increased SWC by about 30%[11].

Tillage also affects SBD, a key indicator of soil structure. In Spain, no-tillage resulted in higher SBD than standard tillage[12] whereas on the North China Plain, subsoiling to 30 cm effectively decreased SBD compared with shallow subsoiling[13]. Deep plowing decreased SBD relative to shallow rotary tillage in Inner Mongolia, China[14] whereas in northeastern China, rotary tillage reduced shallow SBD more effectively than plowing[15]. These findings indicate that identical tillage practices can produce contrasting outcomes across regions, likely due to differences in soil type and climate. Regarding thermal regulation, tillage also influences ST differently under varying climates. For example, no-tillage lowered surface ST in Spain[12] whereas a study in China found that no-tillage maintained significantly higher ST than standard or subsoil tillage[16]. Similarly, tillage practices affect SPR. In Inner Mongolia, shallow rotary tillage reduced SPR more effectively than strip tillage, subsoiling, or deep plowing. Conversely, studies from Iran, Croatia and Malaysia[17-19] consistently reported that no-tillage tends to increase SPR, particularly in deeper soil layers.

Importantly, the Mollisols of northeastern China are characterized by high organic matter content, unique soil structure, and a cold climate with concentrated rainfall during the growing season. These distinct conditions likely mediate soil responses to tillage practices in ways that differ from other regions. However, few studies have systematically examined the effects of rotational tillage following short-term NTSM in this ecologically fragile region.

Therefore, the present study was designed to evaluate the effects of different rotational tillage practices following short-term NTSM on SWC, SBD, ST and SPR at multiple soil depths in the Mollisols region of northeastern China. The results provide region-specific evidence to guide the rational selection of tillage practices, and the development of rotational tillage systems aimed at maintaining and enhancing soil productivity. Ultimately, these findings will contribute to both the effective protection and sustainable utilization of Mollisols in northeastern China.

2 Materials and methods

2.1 Experimental site

The experiment was conducted at the experimental base of northeastern Agricultural University (45.77° N, 126.92° E), located in the central region of the northeastern Mollisols Zone. It has a typical temperate continental monsoon climate, with a cumulative temperature exceeding 10 °C between 2600 and 2700 °C, a frost-free period of 135–145 days, and an average annual precipitation of 550 mm. The positioning experiment was conducted from 2019 to 2022, with soil sampling and physical properties collected in 2022.

The soil type at the experimental site is a silty clay loam, and the soil properties at a depth of 0–35 cm before the experiment were as follows: soil organic matter at 26.8 g·kg^{-1}, alkali-hydrolyzable nitrogen at 139 mg·kg^{-1}, available phosphorus at 19.5 mg·kg^{-1}, available potassium at 185 mg·kg^{-1} and pH 6.03. The rainfall and temperature per day at the experimental site from April to October in 2022 are shown in Fig. 1.

2.2 Experiment design

The experiment was designed under the widely adopted maize-maize-soybean crop rotation system of the Mollisols region of northeastern China. Following 2 years of NTSM, three treatments were implemented: deep plowing (DP), rotary tillage following subsoiling (RTFS) and subsoil tillage (SST). Specific operations of each tillage treatment are given in Table 1. The main operating machinery used in the experiment are shown in Fig. 2.

The maize cultivar used was Tianlong 9, and the soybean cultivar was Heinong 84. The sowing operations were conducted on ridges with a width of 0.65 m. Maize was planted in single rows at 0.25 m spacing, and soybeans were planted in double rows at 0.1 m spacing. Mechanical sowing was conducted alongside the application of nitrogen at 64 kg·ha^{-1}, phosphorus at 42 kg·ha^{-1}, and potassium at 66 kg·ha^{-1}. For all treatments, irrigation relied solely on rainfall. The other field management practices remain consistent at experimental stages to ensure comparability of experiment results.

The experimental plots were designed using the randomized block design. Three replicate plots were set up for each tillage treatment, distributed in different rows and columns, to eliminate errors in experimental data caused by uneven soil characteristics. The experimental area consisted of three experimental columns. The width of each column is 3.9 m (6 ridges) and sampling was conducted in the middle four ridges (2.6 m). Each experimental column was divided into three experimental plots, with 8 m for measuring and 6 m turning areas for agricultural machinery set between adjacent plots and at both ends of each experimental column.

2.3 Soil physical property indices and measurement methods

The experiment was implemented according to the

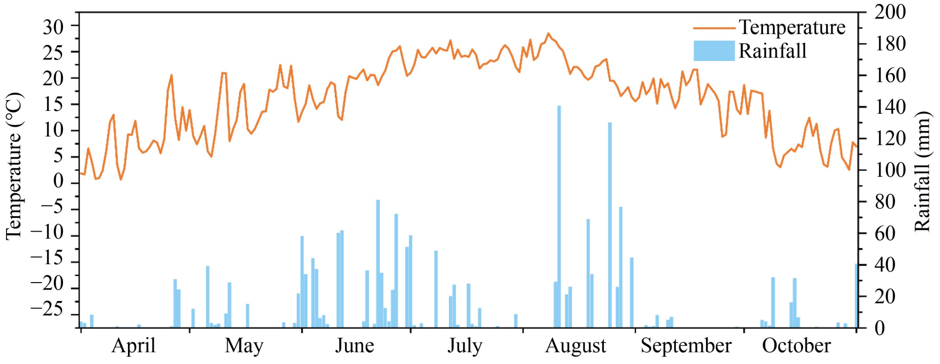


Fig. 1 Rainfall and temperature from April to October 2022 at the experimental site. The data were obtained from the website of the China Meteorological Administration.

Table 1 Specific mechanical operations of each tillage treatment

Implementation year	Treatment	Preceding crop	Specific operation	Immediate crop
2019–2020 2020–2021	No-tillage with straw	Maize	Maize was harvested leaving stubble with the height of 40–60 cm standing in the field in autumn 2019 and 2020, respectively. The 2BMFJ no-tillage precision planter was applied to sow maize or soybean directly without any tillage practice in spring 2020 and 2021, respectively	Maize (2020) Soybean (2021)
2021–2022	Deep plowing	Soybean	Soil and straw were turned over to a depth of 25–30 cm with a moldboard plow after the soybeans were harvested, breaking the clods, then forming ridges in autumn 2021. Maize was sown with a precision planter in spring 2022	Maize (2022)
	Rotary tillage following subsoiling		Subsoiling with a chisel plow over 30 cm deep after the soybeans were harvested, followed by rotary tillage to a depth of 15 cm and then forming ridges in autumn 2021. Maize was sown with a precision planter in spring 2022	
	Subsoil tillage		Subsoiling with a chisel plow over 30 cm deep after the soybeans were harvested, and then forming ridges in autumn 2021. Maize was sown with a precision planter in spring 2022	

Fig. 2 Operating machinery used in the experiment: (a) 2BMFJ no-tillage precision planter (completing straw mulching on the surface); (b) moldboard plow; (c) chisel plow; and (d) rotary cultivator.

aforementioned experimental design methodology. SWC, SBD, ST and SPR were measured at maize the three-leaf (V3, 21 May), six-leaf (V6, 27 June), milk ripe (R3, 2 August), and full ripe (R6, 20 September) stages in 2022.

Undisturbed soil cores were collected from depths of 5, 15, 25 and 35 cm in the plant row (ridge) using stainless steel cylinder samplers (50 mm × 50 mm). Three replicate samples were collected from each soil layer for each treatment. The mass of the aluminum box and soil was weighed using a high-precision balance (LQC-6002, Lenqi, Suzhou Jiangsu; 0.01 g precision). The fresh soil samples were dried in an electric blast drying oven (GFL-230, Labotery, Tianjin; 0.1 °C precision) according to the NY/T 52-1987, with a drying temperature of 105 °C until reaching constant weight. SWC[20] and SBD[21] were determined from the experimental measurements.

ST was measured in each experimental plot using a soil thermometer at the soil surface (ambient temperature) and at four depths of 5, 15, 25 and 35 cm in the plant row. The ST differences (STD) were calculated as:

$$\mathrm{STD} = T_X - T_0 \tag{1}$$

where, T_X is temperature of the x cm soil layer and T_0 is temperature at soil surface at the same plot of T_X.

SPR data were measured using a soil penetration resistance meter (PV6.08, Royal Eijkelkamp, Giesbeek, Netherlands; 0.1 MPa precision) in the cross section in each experimental plot. Seven measurement points were set at 11 cm intervals centered on the plant row laterally, and SPR data were automatically recorded at every 1 cm depth vertically. The soil sampling position and SPR testing cross section are shown in Fig. 3.

2.4 Statistical analysis

Microsoft Excel 2019 software was used to calculate the average

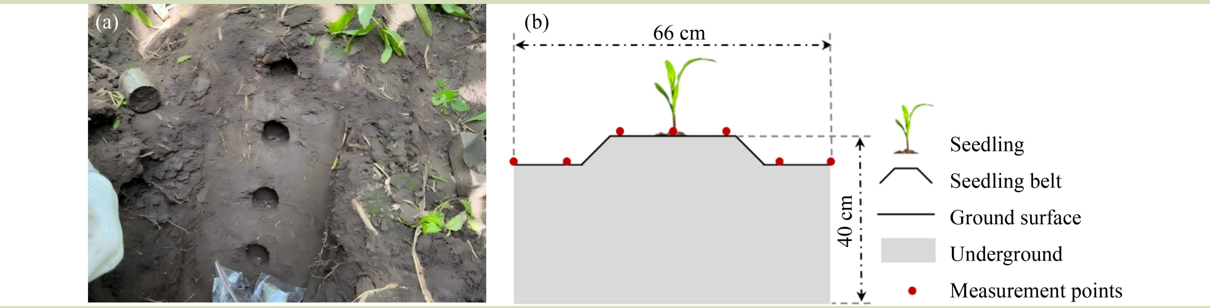


Fig. 3 Soil sampling and SPR testing: (a) soil sample locations for SWC, SBD and ST; and (b) soil cross section for testing SPR.

values of replicate samples for each physical property index. Statistical analyses were performed using SPSS 26.0. One-way analysis of variance was conducted to determine the significance of differences in SWC, SBD, ST, STD and SPR (plant row) between tillage treatments and soil layers. After confirming the assumptions of normality and homogeneity of variances, multiple comparisons were performed using the least significant difference test at a 0.05 probability level.

Line graphs and bar charts were generated in Origin 2018, and contour maps of SPR for each soil cross section were generated in Surfer 23.

3 Results

3.1 Soil water content

3.1.1 Soil water content response with tillage treatments

As shown in Fig. 4, at V3, SWC under RTFS and SST treatments was significantly higher than under DP treatment by 9.8% and 9.0% in the 5-cm soil layer, respectively, and there were no significant differences between RTFS and SST treatments. SWC under DP treatment was significantly higher than under SST treatment by 7.4% in the 25-cm soil layer, and

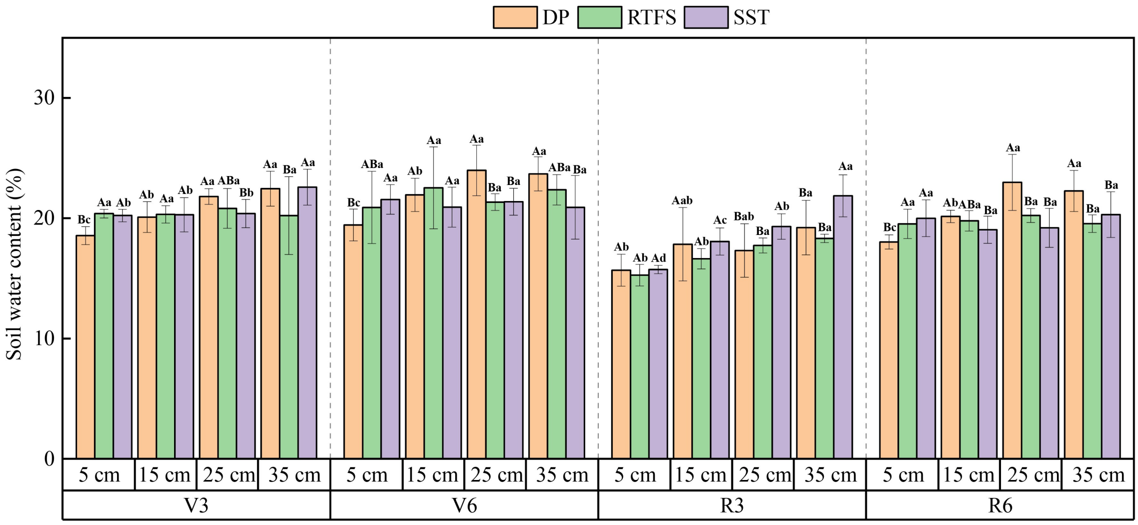


Fig. 4 Soil water content response at the same stage under different tillage treatments and soil depths. Means with the same uppercase letters are not significantly different between treatments within soil depths ($P < 0.05$), and with same lowercase letters, between soil depths within a treatment ($P < 0.05$). V3, three-leaf; V6, six-leaf; R3, milk ripe; R6, full ripe. DP, deep plowing; RTFS, rotary tillage following subsoiling; SST, subsoil tillage.

there were no significant differences between RTFS treatment and the other treatments. SWC under DP and SST treatments was significantly higher than under RTFS treatment by 10.9% and 11.4% in the 35-cm soil layer, respectively.

At V6, SWC under SST treatment was significantly higher than under DP treatment by 10.9% in the 5-cm soil layer, and there were no significant differences between RTFS and the other treatments. SWC under DP treatment was significantly higher than under RTFS and SST treatments by 12.4% and 12.2% in the 25-cm soil layer, respectively. SWC under DP treatment was significantly higher than under SST treatments by 13.3% in the 35-cm soil layer.

At R3, SWC under SST treatment was significantly higher than under DP and RTFS treatments by 11.5% and 8.9% in the 25-cm soil layer, respectively. SWC under SST treatment was significantly higher than under DP and RTFS treatments by 13.7% and 19.3% in the 35-cm soil layer, respectively.

At R6, SWC under RTFS and SST treatments was significantly higher than under DP treatment by 9.9% and 10.9% in the 5-cm soil layer, respectively. SWC under DP treatment was significantly higher than under SST treatment by 5.8% in the 15-cm soil layer. SWC under DP treatment was significantly higher than under RTFS and SST treatments by 13.6% and 19.7% in the 25-cm soil layer, respectively, and by 13.9% and 9.7% in the 35-cm soil layer, respectively.

3.1.2 Soil water content response at soil depths

Similarly, as shown in Fig. 4, at V3, SWC under DP treatment was significantly different between soil layers, with SWC in the 25-cm soil layer significantly higher than in the 5- and 15-cm soil layers by 17.6% and 21.1%, respectively, and SWC in the 35-cm soil layer was significantly higher than in the 5-and 15-cm soil layers by 21.1% and 11.7%, respectively. There were no significant differences in SWC between soil layers under RTFS treatment. SWC in the 35-cm soil layer under SST treatment was significantly higher than in the 5-, 15- and 25-cm soil layers, by 11.67%, 11.3% and 10.8%, respectively.

At V6, SWC in the 25-cm soil layer was significantly higher than in the 5- and 15-cm soil layers by 23.4% and 21.9% under DP treatment, respectively. Also, SWC in the 35-cm soil layer was significantly higher than in the 5- and 15-cm soil layers by 21.7% and 8.0% under DP treatment, respectively. There were no significant differences in SWC between all soil layers under RTFS and SST treatments.

At R3, SWC in the 35-cm soil layer was significantly higher than in the 5-cm soil layer by 22.6% under DP treatment. SWC in the 25-cm soil layer was significantly higher than in the 5- and 15-cm soil layers by 16.2% and 6.7% under RTFS treatment, respectively. Also, SWC in the 35-cm soil layer was significantly higher than in the 5- and 15-cm soil layers by 20.0% and 10.2% under RTFS treatment, respectively. SWC in the 15-, 25- and 35-cm soil layers was significantly higher than in the 5-cm soil layer by 14.8%, 6.9% and 13.2% under SST treatment, respectively.

At R6, the significant differences in SWC between the soil layers under DP treatment were the same as those at V3 and V6. SWC in the 25-cm soil layer was significantly higher than in the 5- and 15-cm soil layers by 27.5% and 14.0%, respectively. There were no significant differences in SWC between soil layers under RTFS and SST treatments.

3.2 Soil bulk density

3.2.1 Soil bulk density response with tillage treatments

As shown in Fig. 5, at V3, SBD under DP and RTFS treatments was significantly lower than under SST treatment by 10.0% and 14.6% in the 5-cm soil layer, respectively, and by 11.9% and 17.0% in the 15-cm soil layer. SBD under DP treatment was significantly lower than under RTFS by 14.3% in the 25-cm soil layer. SBD under DP treatment was significantly lower than under RTFS and SST treatments by 14.2% and 10.2% in the 35-cm soil layer, respectively.

At V6, SBD under DP and RTFS treatments was significantly lower than under SST treatment in the 15- and 35-cm soil layers. SBD under DP treatment was significantly lower than under RTFS and SST treatments by 8.3% and 12.0% in the 25-cm soil layer, respectively.

At R3, SBD under RTFS treatment was significantly lower than under DP treatment by 5.5% in the 5-cm soil layer. SBD under RTFS treatment was significantly lower than under SST treatment by 7.5% in the 25-cm soil layer. SBD under DP and RTFS treatments was significantly lower than under SST treatment by 10.5% and 14.0% in the 35-cm soil layer, respectively.

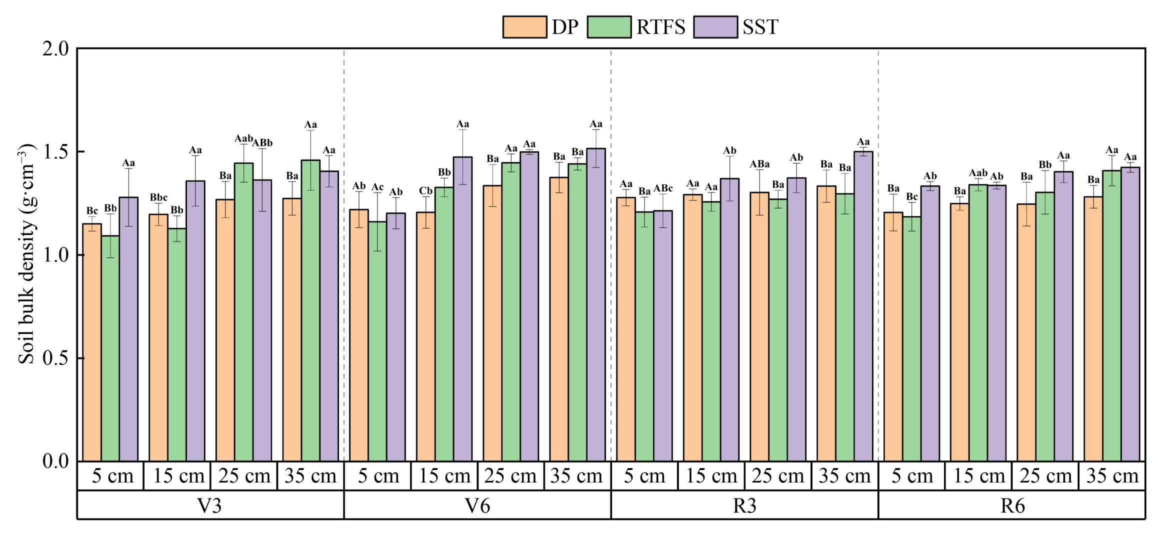


Fig. 5 Soil bulk density response at the same stage under different tillage treatments and soil depths. Means with the same uppercase letters are not significantly different between treatments within soil depths ($P < 0.05$), and with same lowercase letters, between soil depths within a treatment ($P < 0.05$). V3, three-leaf; V6, six-leaf; R3, milk ripe; R6, full ripe. DP, deep plowing; RTFS, rotary tillage following subsoiling; SST, subsoil tillage.

At R6, SBD under DP and RTFS treatments was significantly lower than under SST treatment by 9.6% and 11.1% in the 5-cm soil layer, respectively. SBD under DP treatment was significantly lower than under RTFS and SST treatments in the 15-cm soil layer. SBD under DP and RTFS treatments was significantly lower than under SST treatment by 12.9% and 7.7% in the 25-cm soil layer, respectively. SBD under DP treatment was significantly lower than under RTFS and SST treatments by 9.4% and 10.9% in the 35-cm soil layer, respectively.

3.2.2 Soil bulk density response at soil depths

Similarly, as shown in Fig. 5, at V3, SBD in the 5- and 15-cm soil layers was significantly lower than in the 35-cm soil layer by 10.4% and 5.8% under DP treatment, respectively. SBD in the 5- and 15-cm soil layers was significantly lower than in the 25-cm soil layer by 32.1% and 27.4% under RTFS treatment, respectively. Also, SBD in the 5- and 15-cm soil layers was significantly lower than in the 35-cm by 33.9% and 29.2% under RTFS treatment, respectively. There were no significant differences in SBD between the 5- to 35-cm soil layers under SST treatment.

At V6, SBD in the 5- and 15-cm soil layers was significantly lower than in the 25-cm soil layer by 9.8% and 10.7% under DP treatment, respectively. Similarly, SBD in the 5- and 15-cm soil layers was significantly lower than in the 35-cm soil layer by 12.3% and 13.2%, respectively. SBD in the 25- and 35-cm soil layers was significantly lower than in the 5-cm soil layer under RTFS and SST treatments.

At R3, there were no significant differences in SBD between the 5- to 35-cm soil layers under DP and RTFS treatments. There were no significant differences in SBD between the 15- and 25-cm soil layers under SST treatment whereas SBD in the 5-cm soil layer was significantly lower than in the 35-cm soil layer by 24.0%.

At R6, SBD in the 5-cm soil layer was significantly lower than in the 25- and 35-cm soil layers by 10.2% and 19.5% under RTFS treatment, respectively. SBD in the 5- and 15-cm soil layers was significantly lower than in the 25-cm soil layer by 52.6% and 44.8% under SST treatment, respectively. Also, SBD in the 5- and 15-cm soil layers was significantly lower than in the 35-cm soil layer by 67.7% and 59.7% under SST treatment, respectively.

3.3 Soil temperature and soil temperature difference

3.3.1 Soil temperature response with tillage treatments and at soil depths

As shown in Table 2. There were no significant differences in ST between the tillage treatments at the same growth stage ($P > 0.05$); however, a significant difference was observed between soil layer depths ($P < 0.05$).

At V3, ST in the 25- and 35-cm soil layers was significantly lower than in the 5-cm soil layer by 22.7% and 24.1% under DP treatment, respectively. ST in the 25-cm soil layer was significantly lower than in the 5-cm soil layer by 23.0% under RTFS treatment. ST in the 25-cm soil layer was significantly lower than in the 5-cm soil layer by 16.6% under SST treatment.

At V6, ST in the5- to 35-cm soil layer did not show significant differences under DP and RTFS treatments. ST in the 25- and 35-cm soil layers was significantly lower than in the 5-cm soil layer by 8.1% and 9.8% under SST treatment, respectively.

At R3, ST in the 25- and 35-cm soil layers was significantly lower than in the 5-cm soil layer by 11.3% and 14.0% under DP treatment, respectively. ST in the 35-cm soil layer was significantly lower than in the 5-cm soil layer by 12.0% under RTFS treatment. ST in the 15-cm soil layer was significantly lower than in the 5- and 35-cm soil layers by 5.6% and 11.5% under SST treatment, respectively.

At R6, there were no significant differences in ST between tillage treatments and soil layers.

3.3.2 Soil temperature difference response with tillage treatments

Although there were no significant differences in ST between treatments, and the different tillage treatments might have had varying effects on ST regulation. To explore the regulatory effect of tillage practices on the soil thermal environment, it is necessary to analyze the variations in STD (Fig. 6.)

Across the growth stages and treatments, the ST in each soil layer was lower than the ambient temperature, resulting in negative STD values.

At V3, STD under RTFS treatment was significantly higher than under other treatments in the 5- to 35-cm soil layers. STD under RTFS treatment was significantly higher than under DP and SST treatments by an average of 31.5% and 35.7% in the 5-

Table 2 Soil temperature response under different soil layers and tillage treatments at the same growth stage

Stage	Treatment	Soil layer depth (cm)			
		5	15	25	35
V3	DP	22.0 ± 1.01 a	19.0 ± 1.33 ab	17.2 ± 1.79 b	16.9 ± 2.26 b
	RTFS	20.5 ± 1.26 a	17.7 ± 2.90 a	17.5 ± 0.70 a	17.7 ± 1.91 a
	SST	20.4 ± 2.1 a	18.37 ± 1.15 ab	17.0 ± 0.35 b	17.0 ± 1.30 ab
V6	DP	25.0 ± 0.25 a	23.1 ± 0.31 a	23.6 ± 0.92 a	22.1 ± 0.26 a
	RTFS	24.8 ± 0.4 a	23.9 ± 1.01 a	23.8 ± 0.1 a	23.1 ± 0.21 a
	SST	25.5 ± 1.21 a	24.1 ± 0.91 ab	23.4 ± 0.66 b	23.0 ± 0.4 b
R3	DP	28.1 ± 1.1 a	26.90 ± 0.52 a	24.9 ± 0.61 b	24.1 ± 0.85 b
	RTFS	27.7 ± 2.17 a	26.30 ± 1.25 ab	25.4 ± 0.76 ab	24.4 ± 0.85 b
	SST	27.8 ± 0.76 a	26.3 ± 0.91 a	25.6 ± 0.58 ab	24.6 ± 0.67 b
R6	DP	12.8 ± 0.67 a	11.90 ± 2.08 a	12.2 ± 1.25 a	12.7 ± 1.24 a
	RTFS	12.6 ± 1.36 a	11.37 ± 0.55 a	11.1 ± 0.53 a	11.3 ± 1.14 a
	SST	12.1 ± 0.78 a	11.2 ± 1.40 a	11.8 ± 0.31 a	11.7 ± 0.53 a

Note: There were no significant differences between treatments within a soil depth ($P < 0.05$) and means with the same lowercase letter are not significant different between soil depths within a treatment ($P < 0.05$). V3, three-leaf; V6, six-leaf; R3, milk ripe; R6, full ripe. DP, deep plowing; RTFS, rotary tillage following subsoiling; SST, subsoil tillage.

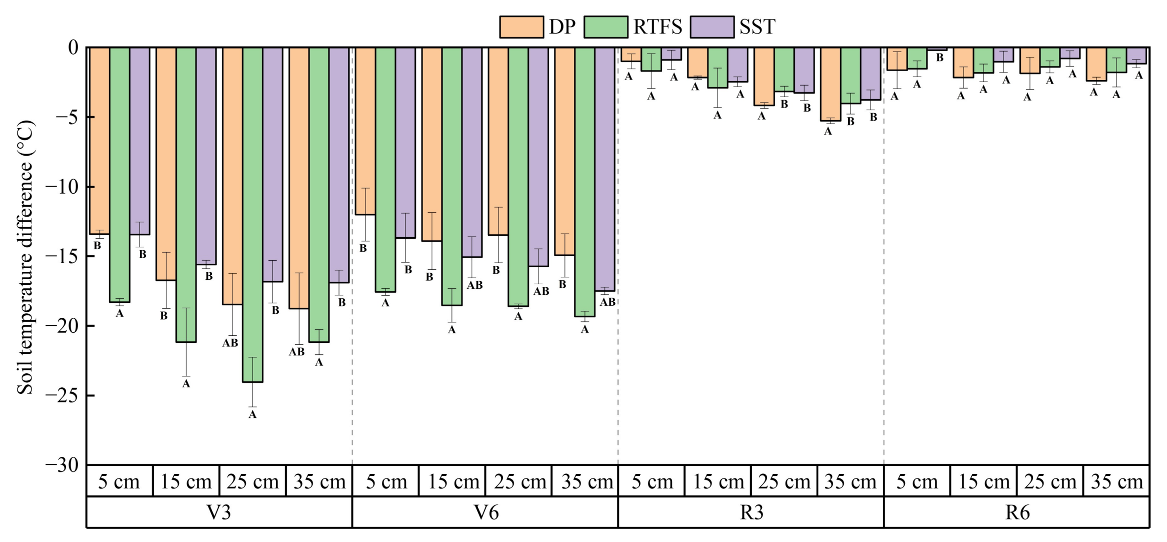


Fig. 6 Soil temperature difference response in the same layer and growth stage under different tillage treatments. Means with the same letter are not significantly different between treatments at the same soil layer ($P < 0.05$). V3, three-leaf; V6, six-leaf; R3, milk ripe; R6, full ripe. DP, deep plowing; RTFS, rotary tillage following subsoiling; SST, subsoil tillage.

and 15-cm soil layers, respectively. STD under RTFS treatment was significantly higher than under SST treatment by 29.8% in the 25-cm soil layer. STD under RTFS treatment was significantly higher than under SST treatment by 25.2% in the 35-cm soil layer.

At V6, STD under RTFS treatment was significantly higher than under DP and RTFS treatments by 46.4% and 28.4% in the 5-cm soil layer, respectively. STD under RTFS treatment was significantly higher than under DP treatment by 33.3% in the 15-cm soil layer. STD under RTFS treatment was significantly higher than under DP treatment by 38.1% in the 25-cm soil layer.

At R3, STD increased with soil depth across all treatments. STD under DP treatment was significantly higher than under RTFS and SST treatments by 31.6% and 27.6% in the 25-cm soil layer, respectively. STD under DP treatment was significantly higher than under RTFS and SST treatments by 30.6% and 39.8% in the 35-cm soil layer.

At R6, temperature differences changed only slightly, ranging from 0.2 to 2.4 °C. STD under DP and RTFS treatments was significantly higher than under SST treatment by 71.7% and 83.3% in the 5-cm soil layer, respectively.

3.4 Soil penetration resistance

3.4.1 Variations in soil cross section soil penetration resistance

SPR data from soil cross section in each experimental plot were used to draw contour maps reflecting the overall variations of SPR. This can be observed from Fig. 7.

At V3 (Fig. 7(a–c)), SPR in to 40 cm was lower under DP treatment compared to RTFS and SST treatments. The effect of DP treatment on SPR throughout the soil cross section was mainly observed to 25 cm, where the soil was loose and structurally uniform, with SPR values ranging from 1.2 to 1.8 MPa. The SPR above 25 cm increased significantly, with values exceeding 2 MPa, indicating that a certain degree of compaction existed in the deep layer. The RTFS treatment mainly reduced SPR to 15 cm, with values ranging from 1.4 to 2.0 MPa. Below the 15-cm layer, SPR values exceeded 2.0 MPa, and localized high SPR values were observed in the furrow area (−33 to −22), indicating uneven soil structure. The SST treatment was the least effective in reducing SPR, with SPR values exceeding 2.0 MPa.

As growth progressed (Fig. 7(d–f)), SPR values decreased under all three treatments, but SPR under both DP and RTFS

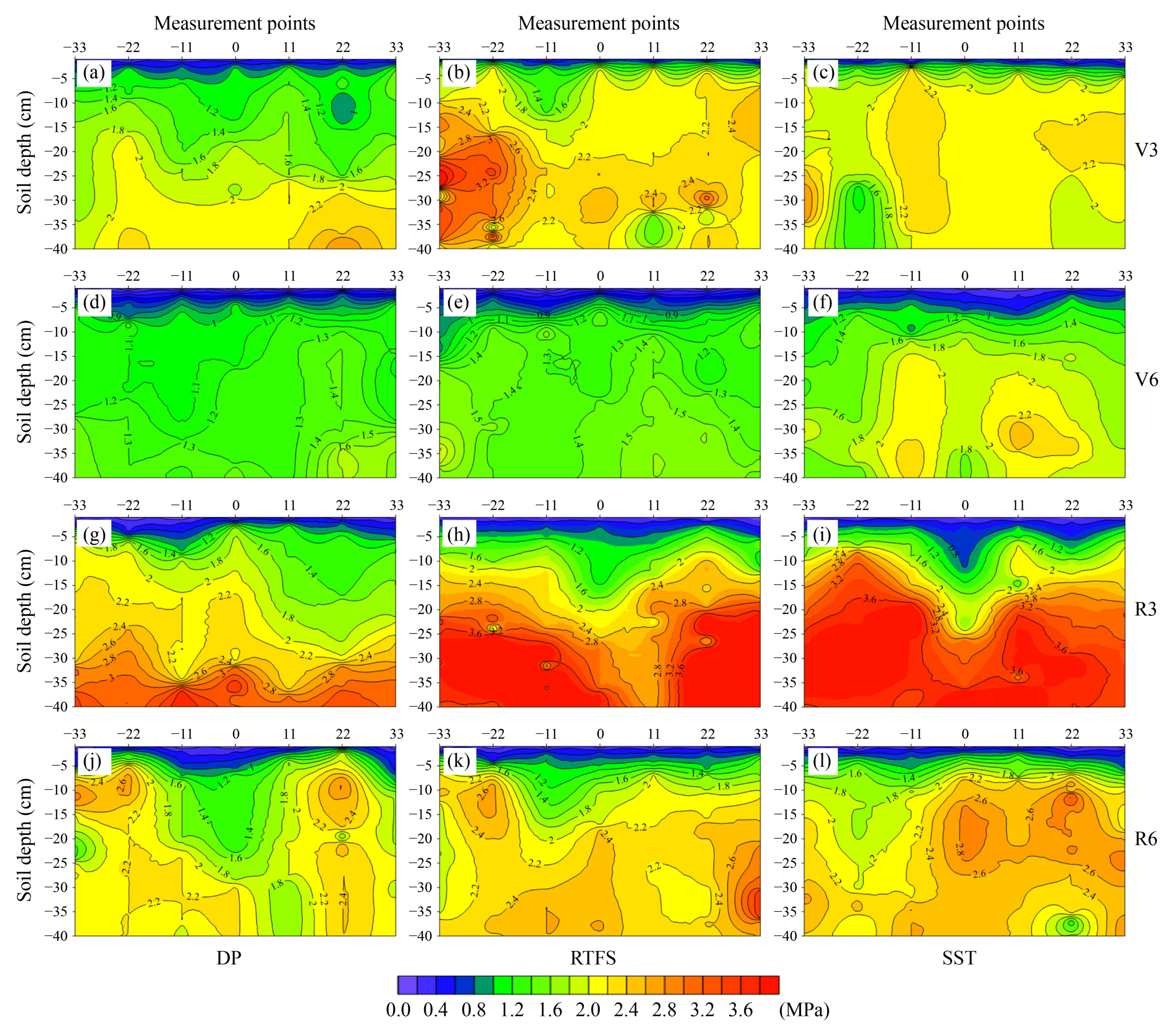


Fig. 7 Soil penetration resistance (SPR) contour maps for all measurements across sections at four growth stages under three tillage treatments. The horizontal coordinates −33 to −22 and 22 to 33 are furrows, and −11 to 11 is the plant row (bridge). (a), (d), (g), (j) are the SPR from V3 to R6 stages under DP treatment, respectively; (b), (e), (h) and (k) are the SPR from V3 to R6 stages under RTFS treatment, respectively; and (c), (f), (i) and (l) are the SPR from V3 to R6 stages under SST treatment, respectively. V3, three-leaf; V6, six-leaf; R3, milk ripe; R6, full ripe. DP, deep plowing; RTFS, rotary tillage following subsoiling; SST, subsoil tillage.

treatments remained lower than under SST treatment at the V6 stage. The SPR range under DP and RTFS treatments was between 1.1 and 1.5 MPa whereas SST treatment had localized high values at 20–40 cm deep, exceeding 2.0 MPa.

At R3 (Fig. 7(g–i)), differences in SPR to 15 cm s between three treatments were minimal, with values ranging from 1.2 to 2 MPa. However, compared to the other treatments, the DP treatment affected deeper soil layers, reaching to 30 cm. In contrast, the RTFS treatment exhibited excessive compaction at 20 cm deep, with SPR values exceeding 2.8 MPa whereas the SST treatment had SPR values exceeding 2.8 MPa at a depth of just 15 cm.

Finally, at R6 (Fig. 7(j–l)), SPR under three treatments ranged from 1.2 to 2.6 MPa. However, SPR under DP treatment was significantly lower than under other treatments in the plant row (−11 to 11). The SST treatment had a large area of high SPR values at 10–25 cm deep, reaching up to 2.6 MPa.

This analysis indicated that DP treatment consistently reduced SPR more effectively across different soil depths and growth stages, particularly in deeper layers. The RTFS treatment had a moderate impact, predominantly improving shallow soil layers. However, the SST treatment resulted in higher compaction levels, especially in deeper layers.

3.4.2 Soil penetration resistance response with tillage treatments and at soil depths

To minimize the influence of wheel compaction and ensure data consistency, the variation in SPR at 5–35 cm deep at three sampling points along the plant rows (Fig. 3(b)) was analyzed under different tillage treatments (Fig. 8).

(1) Soil penetration resistance variations under different tillage treatments within the same soil depth

At V3, SPR under DP treatment was significantly lower than under RTFS and SST treatments by 36.3% and 46.3% in the 5-cm soil layer, respectively. SPR under DP treatment was significantly lower than under SST treatment by 43.7% in the 15-cm soil layer, and by 30.3% in the 25-cm soil layer.

At V6, SPR under DP treatment was significantly lower than under SST treatment by 42.0% in the 15-cm soil layer. SPR under DP treatment was lower than under RTFS and SST treatments by 16.9% and 40.7% in the 25-cm soil layer.

At R3, SPR under DP treatment was significantly lower than under RTFS and SST treatments by 22.8% and 38.7% in the 25-cm soil layer, respectively. SPR under DP and RTFS treatments was significantly lower than under SST treatment by 22.3% and 20.6% in the 35-cm soil layer, respectively.

At R6, SPR under DP treatment was significantly lower than under SST treatment by 36.2% in the 15-cm soil layer and by 22.7% in the 25-cm soil layer.

(2) Soil penetration resistance variations at the same soil depth within the same tillage treatment

At V3, SPR in the 25- and 35-cm soil layers was significantly higher than in the 5-cm soil layer by 56.9% and 86.3% under DP and RTFS treatments. At V6, SPR in the 15- to 35-cm soil layer was significantly higher than in the 5-cm soil layer under three treatments. At R3, SPR in the 35-cm soil layer was significantly higher than in the 5- and 15-cm soil layers by 54.0% and 54.9% under DP treatment, respectively. SPR in the 25- and 35- cm soil layers were significantly higher than in the

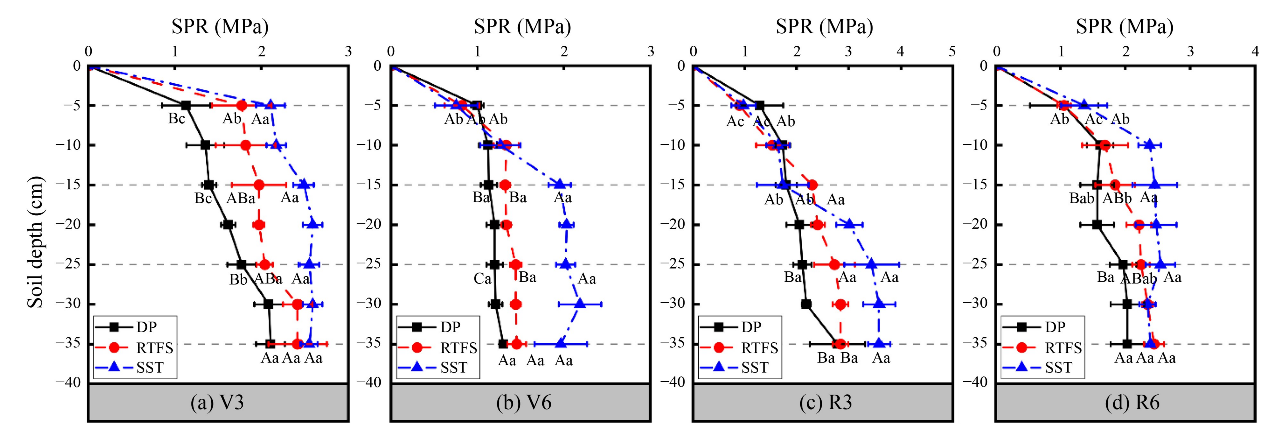


Fig. 8 Soil penetration resistance (SPR) response in the plant row between different tillage treatments and soil layers across growth stages. Capital letters indicate significant differences between different treatments within the same soil layer ($P < 0.05$), and lowercase letters indicate significant differences between different soil layers within the same treatment ($P < 0.05$). (a) SPR at the V3 stage; (b) SPR at the V6 stage; (c) SPR at the R3 stage; and (d) SPR at the R6 stage. V3, three-leaf; V6, six-leaf; R3, milk ripe; R6, full ripe. DP, deep plowing; RTFS, rotary tillage following subsoiling; SST, subsoil tillage.

5-cm soil layer under SST treatment, with a maximum of 3.59 MPa. At R6, SPR in the 25- and 35-cm soil layer was significantly higher than in the 5-cm soil layer under three tillage treatments, increasing by more than 80%.

4 Discussion

4.1 Effect of different tillage treatments on soil water content

Except for R3 stage, SWC in the 5-cm soil layer under RTFS and SST treatments was on average significantly higher than under DP treatment by 10.3% and 8.6% ($P < 0.05$), respectively, indicating that SWC under both RTFS and SST treatments was significantly higher in the 5-cm soil layer. The result was primarily attributed to their operations, which alleviated shallow soil compaction and improved soil infiltration capacity, allowing precipitation to infiltrate the soil more effectively, rather than being lost. However, the shallow soil under DP treatment became excessively loose, leading to rapid infiltration of precipitation into deeper layers or even its loss, resulting in lower SWC[22]. The SWC variation observed in the present study align with the findings of Jiang et al.[23] and Fan et al.[24].

At R3, SWC in the 25- and 35-cm soil layers under SST treatment was significantly higher than under DP and RTFS treatments by 12.7% and 14.2% ($P < 0.05$), respectively. This indicates that SST treatment improved the SWC of the deeper soil more than other treatments under drought conditions (Fig. 1). The finding is consistent with conclusions of Schneider et al.[25] that the water storage effect of subsoiling increases with declining rainfall and rising drought severity, soil water infiltration was increased under SST treatment, which led to a reduction in waterlogging and runoff during stages of heavy rainfall, consequently enhancing water recharge during dry seasons. Additionally, SST treatment helped mitigate drought effects by forming a subsurface reservoir at depths exceeding 30 cm[26].

The results also indicated that SWC in the 25- and 35-cm soil layers was significantly higher than in the 5- and 15-cm soil layer under DP treatment at all maize growth stages ($P < 0.05$), which indicated that DP treatment significantly improved the water storage capacity of the deep soil. According to Scanlon et al.[27] findings, deep plowing alters soil water movement and distribution, boosting deep drainage and redistributing soil water[28,29]. After 2 years of NTSM, deep plowing effectively loosened compacted soil; however, it raised the rate of water loss, so the SWC in the deep soil layer under DP treatment is higher than in the shallow soil[27].

4.2 Effect of different tillage treatments on soil bulk density

The results indicated that SBD in the 5-cm soil layer under RTFS treatment was significantly lower than under SST treatment by an average of 7.3% ($P < 0.05$), except for the V6 stage, indicating that SBD in the shallow layer was significantly reduced under RTFS treatment. The primary reason is that rotary tillage can break up the shallow soil into finer particles, thereby reducing its bulk density. This finding is consistent with previous research in which the SBD to 10 cm deep under rotary tillage was lower compared to other treatments[30].

The results also indicate that, except for the R3 stage, SBD in 25–35 cm soil layer under DP treatment was significantly lower than under RTFS and SST treatments by an average of 5.9% and 9.3% ($P < 0.05$), indicating that DP treatment was generally more effective in reducing SBD in the deep soil layer. This may be attributed to the DP operation breaking the compacted layer formed by 2 years of NTSM and incorporating surface residues into the deeper layers. As a result, SBD decreased[17]. The effect remained consistent throughout the growing stages, indicating that DP treatment had a sustained impact on deep soil structure.

The results indicate that DP treatment maintained a significantly lower SBD in the deep layer (25–35 cm) throughout the maize growing season, reflecting a relatively long-lasting improvement in soil physical condition. Also, Jiang et al.[31] suggested that the sustainability of this effect is related to higher SWC and lower ST.

4.3 Effect of different tillage treatments on soil temperature and temperature difference

Within the same tillage treatment, ST decreased significantly with increasing soil depth across all layers, primarily due to ST becoming less influenced by air temperature as soil depth increases. Bogužas et al.[32] supposed that water is a key factor affecting ST, with lower water content in the topsoil accelerating its warming. The level of ST is affected by the ambient temperature of the ground; the high ambient temperature will heat the shallow soil so that the heat transfers to the deep soil. Given the difference in depth, the transfer rate varies, resulting in lower temperatures as the soil depth increases[33].

At V3 and V6, STD under DP and SST treatments was significantly lower than under RTFS in the 5- to 35-cm soil layers ($P < 0.05$), indicating more stable temperature distribution under these two treatments in the early stages. At R3, STD under RTFS and SST treatments was lower than under DP treatment in the 25- and 35-cm soil layers ($P < 0.05$), indicating that there was a more uniform and potentially favorable thermal profile in deeper layers under SST and RTFS at this stage. These findings indicated that DP treatment promoted soil warming during early growth stages whereas SST treatment contributed to warming and stabilizing deeper soil layers during later stages. This could be due to the differences in how each tillage treatment altered soil structure: DP treatment significantly altered soil heat capacity and thermal conductivity by inverting the soil[34], and some studies indicated that deep plowing reduced soil heat capacity by increasing organic matter content[35], leading to faster soil warming. RTFS treatment may have increased soil fragmentation near the surface, accelerating heat absorption in the deeper layers but resulting in greater vertical variation in temperature. SST appeared to improve soil porosity and continuity in the vertical profile, facilitating downward heat transfer and reducing temperature gradients. This likely contributed to more uniform warming of the subsoil[36,37].

4.4 Effect of different tillage treatments on soil penetration resistance

The results indicated that SPR in the 15- and 25-cm soil layers under DP treatment was on average significantly lower than under RTFS and SST treatments by 18.6% and 33.8% across all maize growth stages ($P < 0.05$). It was indicated that DP treatment can reduce SPR in the 15- and 25-cm soil layers. The primary reason was that the deep loosening effect of the DP treatment disrupted the compacted plow pan formed by 2 years of NTSM, thereby increasing soil porosity and reducing soil strength[38]. In addition, the mechanical action of the moldboard plow inverted the deep soil to the surface and incorporated straw into the deep furrows. This process also increased the proportion of macropores, which directly contributed to the reduction in SPR[39]. Also, DP treatment facilitated the downward migration of surface organic matter, improving the organic matter content in the subsoil. The increase in organic matter was shown to contribute to lower SPR[40].

Of the three treatments, DP treatment had the greatest effect in reducing SPR in the 15- and 25-cm soil layers. In contrast, SST and RTFS treatments had less impact on SPR in deep soil layers, possibly due to their lower soil disruption capacity.

5 Conclusions

In the Mollisols region of northeastern China, short-term NTSM followed by different tillage practices improved soil physical conditions, but with distinct effects. Of the practices, DP consistently enhanced soil water distribution, reduced compaction in deeper layers and improved soil thermal conditions, showing the best overall performance. RT was more effective in loosening shallow soil whereas SST helped maintain soil water and temperature in deeper layers under stress conditions. Overall, adopting DP after 2 years of NTSM appears to be a suitable rotational tillage strategy to improve soil properties and support sustainable agricultural development in this region, though its applicability to other regions requires further verification.

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Compliance with ethics guidelines

Jinyou Qiao, Linding Wei, Yuhang Xu, Jian Sun, and Haitao Chen declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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