Influences of mechanized tillage and sowing modes on soil physical properties, soybean yield and economic benefits in mollisols region of Northeast China

Haitao Chen[1,2,3], Jian Sun[1,2], Yiming Zhang[1,2], Jinyou Qiao[1,2*]

(1. *College of Engineering, Northeast Agricultural University, Harbin 150030, China*;
2. *Heilongjiang Province Technology Innovation Center of Mechanization and Materialization of Major Crops Production, Harbin 150030, China*;
3. *College of Mechanical and Electrical Engineering, East University of Heilongjiang, Harbin 150066, China*)

Abstract: Appropriate mechanized straw returning and tillage sowing techniques were effective means to optimize soil physical properties and enhance agricultural productivity, as well as important measures for the conservation and restoration of mollisols region in Northeast China. Under the condition of full-scale maize straw returning, four mechanized tillage and sowing modes were set, including plough tillage and sowing (PTS), combined tillage and sowing (CTS), no-tillage and sowing (NTS), and no-tillage and sowing with straw mulching (NTSM). In 2020 and 2021, the study investigated the effects of different mechanized tillage and sowing modes on soil physical properties, soybean yield and economic benefits. The results showed that during the pod-setting and pod-filling period of soybean, the NTS and NTSM treatments exhibited better effects on deep soil insulation and shallow soil moisture retention, the soil physical structure of PTS and CTS treatments were relatively ideal. Compared with PTS and CTS treatments, NTS and NTSM treatments significantly increased soil gravimetric water content (SWC) by 2.35% to 7.98% in the 5-15 cm soil layer and increased soil temperature (ST) by 3.94% to 10.42% in the 25-35 cm soil layer (p<0.05), significantly increased soil bulk density (SBD) by 2.98% to 6.72% and significantly reduced soil total porosity (STP) by 3.88% to 6.53% in the 5-25 cm soil layer, and significantly reduced soil gas phase ratio by 8.26% to 6.27% at the 15-25 cm soil layers, which caused soil three-phase ratio (STPR) of PTS and CTS treatment in 15-25 cm soil layer were relatively ideal. The soybean yield of NTSM treatment in 2020 was not significantly different from PTS and CTS treatment (p>0.05), the soybean yield of NTSM treatment in 2021 significantly increased by 7.30% and 5.84% over PTS and CTS treatments, respectively. And the average annual profit per unit area of NTSM treatment increased by 12.84%, 12.41% and 8.57% compared with PTS, CTS and NTS treatments, respectively. Therefore, it was recommended to combine NTSM technique with PTS or CTS technique in a maize-soybean rotation system in mollisols region. The research results provided reference for the selection of appropriate mechanized tillage and sowing techniques in Northeast China's mollisols region and had important guiding significance and practical value for the construction of rational plow layers and the implementation of conservation tillage.

Keywords: mechanized tillage and sowing modes, full-scale straw returning, soil physical properties, soybean yield, economic benefits, mollisols conservation
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1 Introduction

Soybean was an important source of plant protein for humans and an important component of animal feed. It occupied a strategic position in the global food and agricultural economy and was a high-value crop widely cultivated worldwide. Continuous cropping of soybeans increased the probability of disease and pest occurrence, leading to a decrease in yield[1]. Therefore, soybeans were generally rotated with crops such as maize. However, due to the high density of maize straws, and complex maize straw residue left in the fields after harvest severely restrict the high-quality and efficient production of soybean. In high latitude regions, climate conditions constrained the decomposition rate of straw[2], and the problem of maize straw treatment was more prominent. The mollisols region of Northeast China was a typical representative region[3].

Mechanized maize straw returning could effectively increase soil organic matter content, reduce chemical fertilizer input, increased soil water storage by 0.2% to 5.1% and soil available water by 1.2% to 5.7%, increase organic carbon by 22.0% and reduce soil bulk density by 7.0%, thereby improving the crop yield[4,5]. It was an important way to treat maize straw. Currently, three main modes of full-scale maize straw returning were widely adopted in the maize and soybean production areas of Northeast China: straw burying, straw crushing and mixing, and straw mulching[1,6]. Three methods were distinguished based on the two

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Biographies: Haitao Chen, PhD, Professor, research interest: technical equipment of agriculture and biomass materials, Email: htchen@neau.edu.cn; **Jian Sun**, PhD candidate, research interest: production and management of agricultural mechanization, Email: dnsunjian@163.com; **Yiming Zhang**, PhD candidate, research interest: production and management of agricultural mechanization, Email: 18231538638@163.com.
***Corresponding author: Jinyou Qiao**, PhD, Professor, research interest: production and management of agricultural mechanization. College of Engineering, Northeast Agricultural University, Harbin 150030, China. Tel: +86-13244600531, Email:qiaojinyou@163.com.

key operational steps of tillage and sowing, namely plough tillage and sowing, combined tillage and sowing, and no tillage and sowing mode.

The research results indicated that the mechanized plough tillage and sowing mode, and combined tillage and sowing mode had advantages such as loosening the plow layer soil[7], increasing soil porosity, and reducing soil bulk density[8,9], thereby optimizing the soil three-phase ratio structure[10]. However, these tillage and sowing modes had relatively high mechanical energy consumption per unit area. After plough tillage and combined tillage, the straw was buried underground or mixed into the soil, which leaded to a rapid water loss and increased the risk of wind and water erosion[1,11]. Mechanized no-tillage sowing mode minimized soil disturbance and reduced the number of machine passes, effectively alleviating soil compaction damage[12], which could improve total soil water storage by 6.1% to 15.3% before sowing[13]. However, the residue stubble could easily clog the machinery during the operation, which would affect the sowing quality and efficiency, leading to a decline in yields[14]. No-tillage sowing with straw mulching mode was a new no-tillage sowing method that effectively solved the problem of stubble blockage. In the state of high stubble retention after maize harvest, it achieved "side straw clearance to prevent blockage-bed preparation-precise sowing, fertilization, and spraying-synchronized and uniform straw mulching"[15]. High stubble retention during the winter serves as a windbreak and snow stabilizer, while the uniform straw mulching in the spring after sowing improves soil moisture retention and drought resistance, provids a favorable environment for seed germination and crop growth[3].

There were differences in the effects of different mechanized tillage and sowing modes on soil physical properties and crop yield. Most of the existing studies have mainly compared different mechanized plough tillage and sowing mode, combined tillage and sowing mode, no-tillage and sowing modes by testing the soil temperature, moisture content, bulk density, three-phase ratio and other physical characteristics, as well as crop yield indicators[3]. And some literature have identified suitable operational modes for constructing rational plow layers and increasing productivity and efficiency in different regions[16-20]. Some experts believed that mechanized plough tillage and sowing, combined tillage and sowing modes could promote crop yield by improving the soil physical structure[21,22]. But some scholars have the points that the mechanized no-tillage and sowing mode had low input cost and would not reduce production under suitable sowing conditions, with significant economic benefits[15]. However, there was limited research on the comparative analysis of different mechanized tillage and sowing modes on soil physical properties at different soil depths, and no systematic comparison had been reported on mechanized no-tillage sowing with straw mulching mode and other tillage and sowing modes.

Based on comparative experiments in different mechanized tillage and sowing mode plots for two years, this study aimed to explore their effects on soil physical properties at different soil depths, soybean yield, and economic benefits. The findings would provide a theoretical and technical support for the selection of scientifically rational mechanized tillage and sowing modes and a targeted formulation of mollisols protection measures in the mollisols region of Northeast China.

2 Materials and methods

2.1 Study site

The experimental site is located at the Xiangyang Experimental Base of Northeast Agricultural University in Xiangfang District, Harbin, Heilongjiang Province (45°77′N, 126°92′E). It was situated in the central part of the mollisols region in Northeast China and belongs to a typical temperate continental monsoon climate. The annual sunshine hours ranges from 2400 to 2800 h, accumulated temperature above 10°C was between 2600°C and 2700°C, and the frost-free period lasts for 135 to 145 d. The average annual precipitation is 550 mm. The rainfall in 2020 was 750 mm, which was 36% higher than the 30-year average, and the average rainfall in 2021 was 600 mm, which was 9% higher than the 30-year average. The weekly average temperature and rainfall variations in 2020 and 2021 are shown in Figure 1. The physical and chemical properties of the test soil are listed in Table 1.

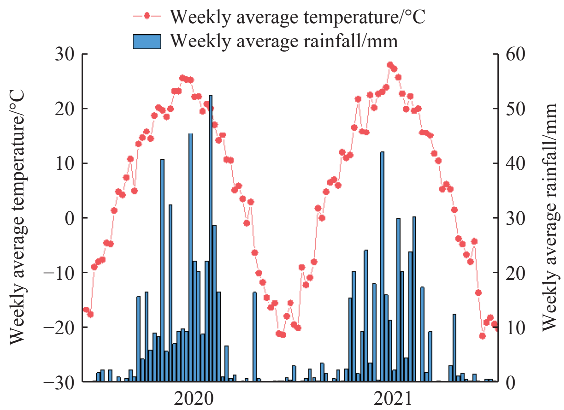


Figure 1 Weekly average temperature and rainfall in test years

Table 1 Physical and chemical properties of test soil

Parameter	Value
Moisture content/%	22.58
Bulk density/g·cm^{-3}	1.40
Soil organic matter/g·kg^{-1}	26.06
Available phosphorus/mg·kg^{-1}	27.64
Available potassium/mg·kg^{-1}	141.20
Ammonium nitrogen/mg·kg^{-1}	21.51
pH	6.09

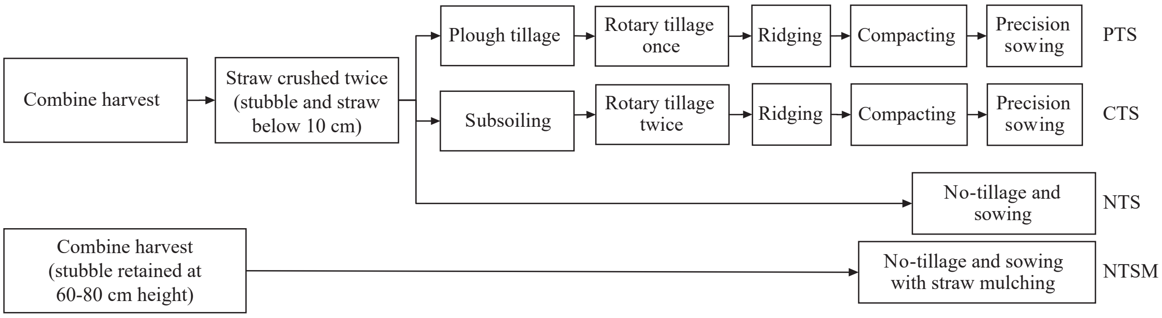
2.2 Experimental design

2.2.1 Determination of experimental plan

The 2-year-repeat experiments for soybean sowing in maize crop plots were conducted from October 2019 to October 2020, and from October 2020 to October 2021. Based on the typical mechanized maize straw handling methods in mollisols region of Northeast China, four mechanized tillage and sowing treatments were set under the condition of full-scale straw returning: plough tillage and sowing (PTS), combined tillage and sowing (CTS), no-tillage and sowing (NTS), and no-tillage and sowing with straw mulching (NTSM). The operational processes of the four treatments are shown in Figure 2.

The maize harvesting and mechanized tillage operations for each treatment were completed in October of 2020 and 2021. From Figure 2, it could be observed that for the PTS, CTS, and NTS treatments, maize was combine harvested meanwhile the maize straw was crushed. Subsequently, the maize straw was mechanized crushed twice using a straw pulverizerr (Hebei Shuangtian Machinery Manufacturing Co., Ltd., China) to ensure that the length of the stubble residue and straw surface cover was below 10 cm. As for the PTS treatment, the soil was plowed with maize stubble buried at a depth of 25-30 cm using a moldboard plough (Heilongjiang Beidahuang Modern Agricultural Service Group

Zhongrong Agricultural Machinery Co., Ltd., China). Rotary tiller (Hebei Shuangtian Machinery Manufacturing Co., Ltd., China) was performed once to break up the soil and level the ground. While for the CTS treatment, subsoiler (Shandong Dahua Machinery Co., Ltd., China) was used to split the soil deep to 30 cm or more, and rotary tiller was performed twice to made the crushed straw was mixed with the soil in the layer of 0-15 cm, and break up the soil and level the ground. Ridges were formed and compacted after above operations of PTS and CTS treatments. The NTS treatment not required any tillage operations after crushing straw. For the NTSM treatment, the maize was combine harvested with maize stubble retained at 60-80 cm height, and not required any tillage operations. The mechanized sowing of soybeans for each treatment were completed in May of 2021 and 2022. The PTS and CTS treatments used the precision seeder (Heilongjiang Bonong Xingda Machinery Co., Ltd., China) for sowing, the NTS treatment used no-tillage seeder (Jiamusi Beixin Machinery Manufacturing Co., Ltd., China) for sowing, and the NTSM treatment used the 2BMFJ-2 precision seeder (Heilongjiang Tuobu Modern Agricultural Equipment Technology Co., Ltd., China) for sowing with straw mulching. No operations shall be carried out during the completion of mechanized tillage preparations and the commencement of mechanized sowing operations for each treatment. And the mechanical operation methods and time for weeding, intertill and other mechanized operations were consistent throughout the experimental period.



Note: PTS, CTS, NTS, and NTSM represent plough tillage and sowing, combined tillage and sowing, no-tillage and sowing, and no-tillage and sowing with straw mulching, respectively.

Figure 2 Mechanized operation processes of different tillage and sowing modes

The soybean variety in the test was Heinong 84, with a seeding rate of 50 kg/hm². Nitrogen fertilizer (N) was applied at a rate of 64 kg/hm², phosphorus fertilizer (P_2O_5) at a rate of 96 kg/hm², and potassium fertilizer (K_2O) at a rate of 80 kg/hm² at the time of sowing. The crop did not receive any irrigation during its growth stage.

2.2.2 Experimental block setup

Each mechanized tillage and sowing treatment was repeated three times. To eliminate potential errors caused by uneven soil distribution within the experimental area, randomized block design was used to ensure that the three repetitions of each treatment were vertically dislocated in three different test blocks. Each block had a length of 36 m, with 6 m buffer zones between test areas and the ends of the test rows to allow the turning or movement of machine. The width of each test blocks were 3.9 m (6 ridges), and the actual testing was conducted in the middle 2.6 m (4 ridges), with the 2 ridges on each side used as protective rows. The experimental area had a total length of 174.0 m, a total width of 11.7 m, and a total area of 2035.8 m².

2.3 Test indicators and methods

2.3.1 Soil physical parameters and testing methods

Following the experimental design mentioned above, soil temperature (ST), soil gravimetric water content (SWC), and soil bulk density (SBD) were measured at depths of 5 cm, 15 cm, 25 cm, and 35 cm during the pod-setting and pod-filling period of soybean (late August). Each parameter was measured three times in each block. Soil total porosity (STP), soil three-phase ratio (STPR), soil three-phase structure distance (STPSD), and generalized soil structure index (GSSI) were calculated based on SWC and SBD.

ST at different depths were measured using a TPJ-21 soil temperature recorder (Zhejiang Topu Yunnong Technology Co., Ltd., China) with an accuracy of 0.5°C. Soil samples of each layer were collected using a ring knife method[23]. Soil water content and soil bulk density were determined in the laboratory using an aluminum box drying method[24], as calculated in Equation (1) and (2).

$$\mathrm{SWC}=\frac{(G_1-G_2)}{(G_2-G_0)}\times 100\% \tag{1}$$

$$\mathrm{SBD}=\frac{100\times(G_1-G_0)}{V\left(100+\mathrm{SWC}\right)} \tag{2}$$

where, G_0 represents the weight of the aluminum box (in grams), G_1 represents the combined weight of the moist soil and aluminum box (in grams), G_2 represents the weight of the dry soil and aluminum box (in grams), and V represents the volume of the ring knife (100 cm³).

Based on the results of SWC and SBD calculated in Equations (1) and (2), STP, STPR, STPSD, and GSSI were calculated by Equations (3)-(6).

$$\mathrm{STP}=\left(1-\mathrm{SBD}/2.65\right)\times 100\% \tag{3}$$

$$X_S : X_L : X_G = (100\% - \mathrm{STP}) : (\mathrm{SWC}\times\mathrm{SBD}) : (\mathrm{STP}-\mathrm{SWC}\times\mathrm{SBD}) \tag{4}$$

$$\mathrm{STPSD}=\left[(X_S-50)^2+(X_S-50)(X_S-25)+(X_L-25)^2\right]^{0.5} \tag{5}$$

$$\mathrm{GSSI}=[(X_S-25)X_L\times X_G]^{0.4769} \tag{6}$$

where, X_S represents the percentage of solid phase volume (>25%), X_L represents the percentage of liquid phase volume (>0%), and X_G represents the percentage of gas phase volume (>0%).

2.3.2 Measuring procedure for soybean yield and economic benefits

During the harvest period of soybeans, an 2 m² area of the middle two ridges within each test block were randomly selected as the yield measurement area. Soybeans were manually harvested and threshed in each test block, and random sampling was performed 3 times with each sample consisting of 20 soybean seeds. The average moisture content of the soybean seeds was determined using the aluminum box drying method, and the soybean yield per hectare was calculated by Equation (7)[25].

$$M_b = \frac{10^4}{S} \times \frac{M(1-F)}{1-F_b} \tag{7}$$

where, M_b represents the soybean yield at standard moisture content, kg/hm²; M represents the measured soybean mass in the test block, kg/m²; S represents the sampling area, m²; F represents the actual SWC of the tested soybean seeds, %; F_b represents the standard SWC of soybeans (F_b=13%).

The economic benefit of soybean was related to the cost of machine operations, agricultural materials input, soybean yield and its selling price, as calculated in Equation (8).

$$EB_S = M_b \times P_S - C_M - C_A \tag{8}$$

where, EB_S represents the per unit economic benefit of soybean, (CNY/hm²); P_S represents the price of soybean, (CNY/kg); C_M represents the per unit cost of machine operations, (CNY/hm²); C_A represents the per unit cost of agricultural materials input, (CNY/hm²).

Among them, the soybean yield was obtained through the experiment, the soybean price was determined according to the market situation, the cost of machine operations and agricultural materials input were calculated according to the actual input of the experiment.

2.4 Statistica analysis

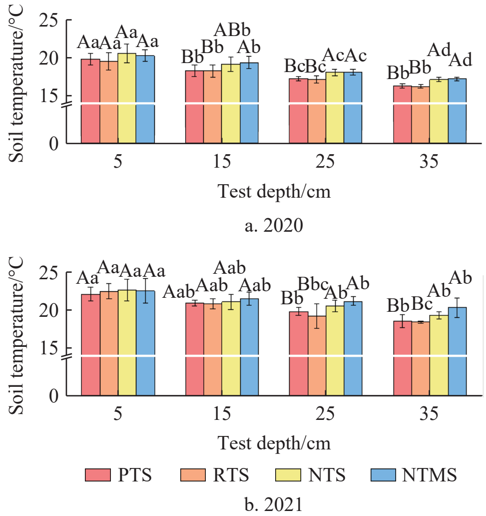
SPSS 23.0 was used to perform multiple comparisons using the Least Significant Difference (LSD) test (p=0.05). Origin 2016 software was used to create line graphs and bar charts to illustrate the variations in soil physical parameters and soybean yield among different treatments and soil depths.

3 Results and analysis

3.1 Influence of mechanized tillage and sowing modes on soil temperature

The soil temperature (ST) of different mechanized tillage and sowing modes is shown in Figure 3. In 2020 and 2021, the ST of all four treatments decreased with increasing soil depth in the 5-35 cm soil layer. In 2020, significant differences in ST were found between the adjacent soil depths for all four treatments (p<0.05). Compared to the ST at 5 cm depth, the ST at 15-35 cm depth showed a significantly decrease by an average of 12.66%, 11.92%, 11.79%, and 9.97% in the PTS, CTS, NTS, and NTSM treatments, respectively. In 2021, no significant differences in ST were found between the adjacent soil depths for all four treatments (p>0.05). Compared to the ST at 5 cm depth, the ST at 25-35 cm depth showed a significantly decrease by an average of 13.18%, 16.24%, 11.87%, and 7.94% in the PTS, CTS, NTS, and NTSM treatments, respectively.

In both 2020 and 2021, the NTS and NTSM treatments had a higher ST than PTS and CTS treatments at the same soil layer. And there were no significant differences in ST at the same soil depth between the PTS and CTS treatments, as well as between the NTS and NTSM treatments. In 2020, there were no significant differences in ST at 5 cm depth among the four treatments. Compared to the PTS and CTS treatments, the ST of NTS treatment showed a significantly increase by an average of 4.64% and 5.11% at the 25-35 cm depths, respectively, and the ST of NTSM treatment showed a significantly increase by an average of 5.37% and 5.84% at the 25-35 cm depths, respectively. In 2021, there were no significant differences in ST at the 5 cm and 15 cm depths among the four treatments. Compared to the PTS and CTS treatments, the ST of NTS treatment showed a significantly increase by an average of 3.94% and 5.94% at the 25-35 cm depths, respectively, and the ST of NTSM treatment showed a significantly increase by an average of 8.17% and 10.24% at the 25-35 cm depths, respectively.



Note: PTS, CTS, NTS, and NTSM represent plough tillage and sowing, combined tillage and sowing, no-tillage and sowing, and no-tillage and sowing with straw mulching, respectively. Different capital letters indicate significant difference between different tillage and sowing modes under the same soil layer (p<0.05). Different lowercase letters indicate significant difference between different soil layers under the same tillage and sowing modes (p<0.05). Same below.

Figure 3 Change of soil temperature in difference mechanized tillage and sowing modes during the pod-setting and pod-filling period of soybean

3.2 Influence of mechanized tillage and sowing modes on soil water content

The soil water content (SWC) of different mechanized tillage and sowing modes are shown in Figure 4. In both 2020 and 2021, the SWC for the same treatment increased in the 5-35 cm soil layer. In 2020, compared to SWC at the 35 cm depth, there were no significant differences in SWC for the PTS, CTS, NTS, and NTSM treatments at the 25 cm depth. However, SWC was showed a significantly decrease by an average of 8.66%, 9.02%, 7.45%, and 7.09% (P<0.05) in the 5-15 cm depth, respectively. In 2021, compared to SWC at the 35 cm depth, there were no significant differences in SWC for the PTS, CTS, NTS, and NTSM treatments at the 25 cm depth. However, SWC showed a significantly decrease by an average of 12.54%, 10.97%, 6.04%, and 8.08% in the 5-15 cm depth, respectively.

In both 2020 and 2021, the NTS and NTSM treatments had a higher SWC than PTS and CTS treatments at the same soil layer. And there were no significant differences in SWC at the same soil depth between the PTS and CTS treatments, as well as between the NTS and NTSM treatments. In 2020, compared to the PTS and CTS treatments, the SWC of NTS treatment showed a significantly increase by an average of 4.18% and 4.53% at the 5-15 cm depths, respectively, and the SWC of NTSM treatment showed a significantly increase by an average of 3.35% and 3.69% at the 5-15 cm depths, respectively. There were no significant differences in SWC at the 25 cm and 35 cm depths among the four treatments. In 2021, compared to the PTS and CTS treatments, the SWC of NTS treatment showed a significantly increase by an average of 6.82% and 7.98% at the 5-15 cm depths, respectively, and the SWC of NTSM treatment showed a significantly increase by an average of 5.50% and 6.06% at the 5-15 cm depths, respectively. There were no significant differences in SWC at 35 cm depth among the four treatments.

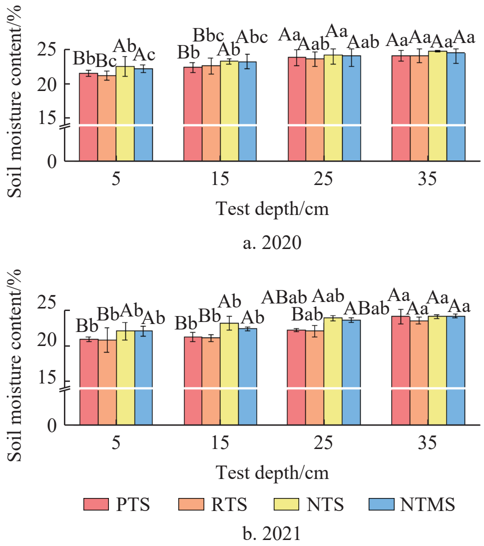


Figure 4 Change of soil moisture in different mechanized tillage and sowing modes during the pod-setting and pod-filling period of soybean

3.3 Influence of mechanized tillage and sowing modes on soil bulk density and total porosity

The soil bulk density (SBD) and total porosity (STP) of different mechanized tillage and sowing modes are listed in Table 2. In 2020 and 2021, SBD increased and STP decreased with increasing soil depth in the 5-35 cm soil layer for the PTS, CTS, and NTSM treatments. However, there was no significant difference in SBD and STP between 15 cm and 25 cm depths of the four treatments (except for PTS treatment in 2020).

In both 2020 and 2021, the four treatments showed the same significant difference between SBD and SPT, the NTS and NTSM treatments had higher SBD and lower STP than the PTS and CTS treatments in the same soil layer. Compared to the NTS and NTSM treatments, the PTS and CTS treatments showed a significantly decrease in SBD and increase in STP at the 5 cm, 15 cm, and 25 cm depths. There were no significant differences in SBD and STP at 35 cm depth among the four treatments. In 2020, compared to the PTS and CTS treatments, the SBD of NTS treatment showed a significantly increase by an average of 5.69% and 6.27% at 5-25 cm soil layers, respectively, and the STP of NTS treatment showed a significantly decrease by an average of 6.53% and 4.51% at the 5-25 cm depths, respectively. The SBD of NTSM treatment showed a significantly increase by an average of 2.98% and 3.54%, respectively, and the STP of NTSM treatment showed a significantly decrease by an average of 4.95% and 3.89% at the 5-25 cm depths, respectively. In 2021, compared to the PTS and CTS treatments, the SBD of NTS treatment showed a significantly increase by an average of 4.44% and 4.71% at the 5-25 cm depths, respectively, and the SBD of NTS treatment showed a significantly decrease by an average of 3.88% and 4.15% at the 5-25 cm depths, respectively. The SBD of NTSM treatment showed a significantly increase by an average of 3.92% and 4.19% at the 5-25 cm depths, respectively, and the STP of NTSM treatment showed a significantly decrease by an average of 3.88% and 4.15% at the 5-25 cm depths, respectively.

Table 2 Change of soil bulk density and total porosity in different mechanized tillage and sowing modes during the pod-setting and pod-filling period of soybean

Year	Test depth/cm	Bulk density/g·cm^{-3}				Soil total porosity/%			
		PTS	CTS	NTS	NTSM	PTS	CTS	NTS	NTSM
2020	5	1.15±0.09^{Bd}	1.13±0.11^{Bc}	1.23±0.10^{Ac}	1.19±0.08^{Ac}	57.60±1.81^{Aa}	57.43±0.45^{Aa}	53.54±3.92^{Ba}	55.13±0.92^{Ba}
	15	1.25±0.07^{Bc}	1.24±0.08^{Bb}	1.30±0.06^{Abc}	1.28±0.06^{Ab}	54.24±1.51^{Ab}	52.24±2.99^{Ab}	50.92±2.37^{Bab}	51.46±2.43^{Bb}
	25	1.29±0.04^{Bb}	1.30±0.05^{Bb}	1.37±0.06^{Aab}	1.33±0.05^{Ab}	51.41±1.40^{Ac}	50.11±1.84^{Ab}	48.13±2.45^{Bbc}	48.58±1.97^{Bb}
	35	1.36±0.03^{Aa}	1.40±0.06^{Aa}	1.45±0.08^{Aa}	1.41±0.06^{Aa}	48.83±1.25^{Ad}	47.21±2.38^{Ac}	45.46±2.98^{Ac}	46.78±2.27^{Ac}
2021	5	1.20±0.07^{Bc}	1.20±0.02^{Bc}	1.29±0.10^{Ac}	1.27±0.02^{Ac}	54.58±0.26^{Aa}	54.56±0.63^{Aa}	51.44±1.34^{Ba}	51.75±0.76^{Ba}
	15	1.31±0.06^{Bb}	1.30±0.01^{Bb}	1.36±0.12^{Ab}	1.34±0.03^{Ab}	50.65±0.88^{Ab}	51.03±0.29^{Ab}	48.84±1.13^{Bb}	49.37±0.97^{Bb}
	25	1.32±0.01^{Bb}	1.32±0.04^{Bb}	1.35±0.02^{Abc}	1.37±0.01^{Aab}	50.16±0.19^{Ab}	50.24±0.37^{Ab}	49.08±0.93^{Bab}	48.24±0.42^{Bbc}
	35	1.40±0.02^{Aa}	1.40±0.03^{Aa}	1.43±0.02^{Aa}	1.43±0.04^{Aa}	41.17±0.69^{Ac}	47.70±1.25^{Ac}	45.97±0.65^{Ac}	46.02±1.60^{Ac}

Note: PTS, CTS, NTS, and NTSM represent plough tillage and sowing, combined tillage and sowing, no-tillage and sowing, and no-tillage and sowing with straw mulching, respectively. Different capital letters indicate significant difference between different tillage and sowing modes under the same soil layer (p<0.05). Different lowercase letters indicate significant difference between different soil layers under the same tillage and sowing modes (p<0.05).

3.4 Influence of mechanized tillage and sowing modes on soil three-phase ratio

3.4.1 Influence of the mechanized sowing mode on composition of soil three-phase ratio

The soil three-phase ratio (STPR) of different mechanized tillage and sowing modes are shown in Figure 5. In 2020 and 2021, the solid phase and liquid phase ratios of the soil increased with the increasing soil depth, while the gas phase ratio decreased with the increasing soil depth.

In both 2020 and 2021, the NTS and NTSM treatments had higher solid phase ratio and liquid phase ratio, and lower gas phase ratios than PTS and CTS treatments at the same depths. There were no significant differences in the STPR at the same depths for the NTSM and NT treatments. The solid phase ratios and liquid phase ratios were similar at the same soil depth for the PTS, CTS, and NTSM treatments. There were no significant differences in the STPR at the same soil depth between the PTS and CTS treatments, as well as between the NTS and NTSM treatments. In 2020, compared to the PTS and CTS treatments, the gas phase ratios of NTS treatment showed a significantly decrease by an average of 25.97% and 25.00% at the 15-25 cm depths, respectively, and the gas phase ratios of NTSM treatment showed a significantly decrease by an average of 14.86% and 8.26% at the 15-25 cm depths, respectively. In 2021, compared to the PTS and CTS treatments, the gas phase ratios of NTS treatment showed a significantly decrease by an average of 12.73% and 20.66% at the 15-25 cm depths, respectively, and the gas phase ratios of NTSM treatment showed a significantly decrease by an average of 13.83% and 21.67% at the

15-25 cm depths, respectively.

3.4.2 Influence of mechanized sowing and cultivation modes on soil three-phase ratio evaluation parameters

STPSD and GSSI indicators were important parameters for assessing soil structure. The closer the soil three-phase structure was to the ideal state, the closer STPSD was to 0, and the closer GSSI was to 100. The STPSD and GSSI indicators of different mechanized tillage and sowing modes are listed in Table 3.

In 2020 and 2021, compared to 5 cm depth, the PTS and CTS treatments showed no significant differences in STPSD and GSSI at the 15 cm and 25 cm depths (p>0.05), but showed a significantly decrease in STPSD and decrease in GSSI at the 35 cm depth (p<0.05), indicating that the PTS and CTS treatments achieved relatively ideal STPR at the 5 cm, 15 cm, and 25 cm depths. Compared to 5 cm depth, the NTS treatment showed a significantly increase in STPSD, and significant decreases or no significant differences in GSSI at the depths of 15 cm, 25 cm, and 35 cm, indicating that the NTS treatment achieved relatively ideal STPR at the depth of 5 cm. Compared to 5 cm depth, the NTSM treatment showed significant increases in STPSD, and a significantly decrease or no significant differences in GSSI at the depths of 15 cm, 25 cm, and 35 cm, indicating that NTSM treatment achieved relatively ideal STPR at the depth of 5 cm.

In both 2020 and 2021, the treatments that achieved relatively ideal STPR at the same soil depth were consistent. Compared to the PTS and CTS treatment, the NTS and NTSM treatments showed a significantly increase in STPSD and a significantly decrease in GSSI at the15 cm and 25 cm depths. This indicated that the PTS and CTS treatments achieved relatively ideal STPR at the 15 cm and 25 cm depths. There were no significant differences in STPSD and GSSI at the 5 cm and 35 cm depths among the four treatments, indicating that the STPR at 5 cm and 35 cm depths for all four treatments were similar.

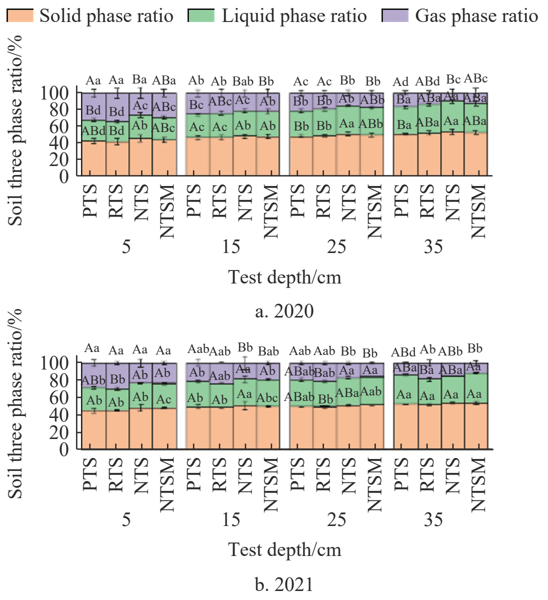


Figure 5 Change of soil three-phase ratio in different mechanized tillage and sowing modes during the pod-setting and pod-filling period of soybean

Table 3 Change of soil three-phase ratio evaluation parameters in different mechanized tillage and sowing modes during the pod-setting and pod-filling period of soybean

Year	Test depth/cm	Soil three-phase structure distance (STPSD)				Generalized soil structure index (GSSI)			
		PTS	CTS	NTS	NTSM	PTS	CTS	NTS	NTSM
2020	5	4.02±2.34^{Ab}	5.01±0.84^{Ab}	6.17±2.36^{Ac}	4.65±0.91^{Ac}	97.75±3.25^{Aa}	98.14±0.92^{Aa}	96.62±2.59^{Aa}	97.60±0.65^{Aa}
	15	3.95±1.27^{Bb}	5.26±1.37^{Bb}	8.69±2.01^{Ab}	5.27±1.89^{Ab}	98.62±0.96^{Aa}	97.62±1.30^{Aa}	92.05±2.14^{Bb}	97.47±2.13^{Ba}
	25	5.49±1.94^{Bb}	6.56±1.34^{Bb}	9.52±2.51^{Ab}	7.50±2.30^{Ab}	97.41±1.66^{Aa}	96.44±1.31^{Aa}	91.25±5.35^{Bb}	94.93±3.23^{Ba}
	35	8.36±2.07^{Ba}	10.47±2.42^{ABa}	13.75±4.03^{Aa}	11.57±4.58^{ABa}	93.69±3.49^{Ab}	89.25±6.12^{Ab}	82.43±13.71^{Ac}	83.99±12.55^{Ab}
2021	5	4.09±0.26^{Ab}	4.80±1.22^{Ab}	3.11±0.47^{Ac}	3.07±1.00^{Ac}	98.66±0.17^{Aa}	98.17±0.87^{Aa}	99.27±0.21^{Aa}	99.32±0.50^{Aa}
	15	3.92±0.37^{Bb}	2.07±0.38^{Bb}	7.15±0.99^{Ab}	5.43±1.19^{Ab}	98.84±0.24^{Aa}	99.68±0.11^{Aa}	95.71±1.27^{Bab}	97.52±1.07^{Bb}
	25	4.29±0.18^{Bb}	4.18±1.40^{Bb}	7.77±1.65^{Ab}	8.40±0.86^{Ab}	98.60±0.12^{Aa}	98.88±0.93^{Aa}	94.83±2.06^{Bb}	93.98±1.36^{Bb}
	35	10.46±0.66^{Aa}	9.03±1.85^{Aa}	12.86±0.95^{Aa}	12.11±2.21^{Aa}	90.22±1.33^{Ab}	92.52±3.13^{Ab}	84.00±2.90^{Ac}	85.15±6.96^{Ac}

Note: PTS, CTS, NTS and NTSM represent plough tillage and sowing, combined tillage and sowing, no-tillage and sowing, and no-tillage and sowing with straw mulching, respectively. Different capital letters indicate significant difference between different tillage and sowing modes under the same soil layer (p<0.05). Different lowercase letters indicate significant difference between different soil layers under the same tillage and sowing modes (p<0.05).

3.5 Influence of mechanized tillage and sowing modes on soybean yield and economic benefits

3.5.1 Influence of mechanized tillage and sowing modes on soybean yield

The soybean yield of different mechanized tillage and sowing modes were shown in Figure 6. Four treatments exhibited higher soybean yields in 2021 than in 2020. And there were no significant differences in soybean yield at the same soil depth between the PTS and CTS treatments, as well as between the NTS and NTSM treatments. In 2020, the PTS and CTS treatments had higher soybean yield than NTS and NTSM treatments. Compared to the PTS and CTS treatments, the soybean yield of NTS treatment showed a significantly increase by 8.13% and 6.11% (p<0.05), respectively, while there was no significant difference (p>0.05) in soybean yield with NTSM treatment. In 2021, the PTS and CTS treatments had lower soybean yield than NTS and NTSM

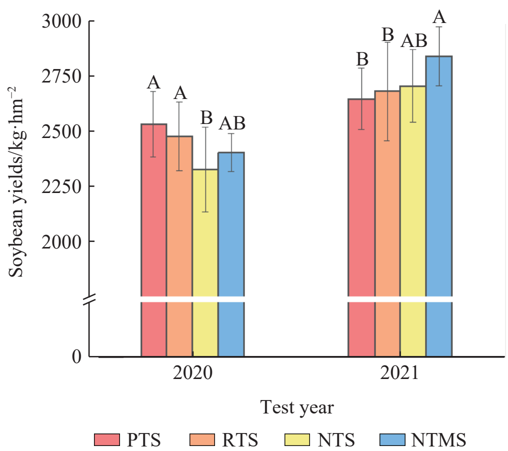


Figure 6 Change of soybean yield in different mechanized tillage and sowing modes

treatments. Compared to the PTS and CTS treatments, there was no significant difference in soybean yield with NTS treatment, and the soybean yield of NTSM treatment showed a significantly increase by 7.30% and 5.84%, respectively.

3.5.2 Influence of mechanized tillage and sowing modes on economic benefits

Based on surveys, the unit area costs of various field operations and agricultural inputs are listed in Table 4. Combining the soybean yield for each treatment shown in Figure 6 and a fixed soybean price of 6 CNY/kg, the sales revenue per unit area was calculated for 2020 and 2021. The profit per unit area for 2020 and 2021 is also listed in Table 4.

From Table 4, it could be observed that among the four mechanized tillage and sowing modes, the NTSM treatment had the lowest combined cost per unit area for mechanized operations. The PTS, CTS, and NTS treatments were 2.60, 2.46, and 1.46 times higher than the NTSM treatment, respectively. In the test year, NTSM treatment had the highest annual profit in the four mechanized tillage and sowing modes. Compared with PTS, CTS, and NTS treatment, the annual profit of NTSM treatment increased by 4.16%, 6.40%, and 7.79% in 2020, respectively, and by 20.98%, 17.79%, and 9.21% in 2021, respectively.

Table 4 Each operation project cost and profit of different tillage and sowing modes

Item		Price per unit area/CNY·hm^{-2}			
		PTS	CTS	NTS	NTSM
The cost of mechanized operations	Combine harvest/Combine harvest with maize stubble at a high level	346.50	346.50	346.50	277.20
	Crushing maize straw twice	300.00	300.00	300.00	-
	Plough tillage/Combined tilling	450.00	346.50	-	-
	Rotary tillage twice	274.00	274.00	-	-
	Ridging	126.00	126.00	-	-
	Compacting	47.25	47.25	-	-
	Precision sowing/No-tillage and sowing No-tillage and sowing with straw mulching	180.00	180.00	200.00	220.00
	Mechanized field management operations	269.63			
	Total	1993.43	1889.93	1116.13	766.83
Agricultural input		2521.00			
Annual profit	2020	10 682.90	10 458.41	10 323.95	11 127.67
	2021	11 375.25	11 683.11	12 601.78	13 761.91

Note: PTS, CTS, NTS and NTSM represent plough tillage and sowing, combined tillage and sowing, no-tillage and sowing, and no-tillage and sowing with straw mulching, respectively.

4 Discussion

4.1 Influence of mechanized tillage and sowing modes on soil physical properties

4.1.1 Influence of mechanized sowing and cultivation modes on soil hydrothermal characteristics

Among various growth stages of soybean, the pod-filling stage was known to have the longest duration and the highest water consumption[26]. Maintaining SWC and ST within the suitable range was crucial for ensuring optimal soybean yield.

The experimental results indicated that during the pod-setting and pod-filling stage of soybean in the experimental year, SWC increased with the increasing soil depth for the four treatments. Compared to the SWC in the 35 cm soil layers, the four treatments exhibited a significant decrease in SWC in the 5-15 cm (p<0.05) soil layers, but the decrease was more pronounced for the PTS and CTS treatments compared to the NTS and NTSM treatments. Therefore, the NTS and NTSM treatments demonstrated better moisture retention in the shallow soil layer. The result above could be attributed to the surface coverage of maize straw residue after the NTS and NTSM treatments, which effectively blocked direct solar radiation on the soil, thereby minimizing soil moisture evaporation and enhancing water retention capacity[14]. These findings were consistent with previous studies[14] that had demonstrated the significant improvement of soil moisture content through conservation tillage practices. In the experimental year, the four treatments showed a decrease in ST with increasing soil depth. Compared to the ST in the 5 cm soil layer, the four treatments showed a significantly decrease in SWC in the 25-35 cm soil layers. However, the decrease was more pronounced for the PTS and CTS treatments compared to the NTS and NTSM treatments in the 25 cm and 35 cm soil layers. Therefore, the NTS and NTSM treatments demonstrated better soil insulation in the deep soil layer. This could be attributed to the straw mulching applied in the NTS and NTSM treatments, which increased the SWC in all soil layers, thereby increasing soil thermal capacity and resulting in a slower change in soil temperature with the increasing soil depth. The findings above were consistent with the conclusion from previous research[27,28] that straw mulching effectively stabilizes soil temperature fluctuations.

In the experimental year, compared to the PTS and CTS treatments, the NTS and NTSM treatments showed a significantly increase by an average of 2.35% to 7.98% in SWC in the 5-15 cm soil layers[7]. The result above was owed to that the PTS and CTS treatments left the soil surface exposed, resulting in more water loss from the loose soil. The straw mulching also increased the surface roughness, effectively reducing surface runoff[17]. Additionally, maize straw had the capacity to absorb water up to 3-4 times its own dry weight[29]. During periods of abundant natural rainfall, the straw mulch uniformly distributed on the surface, could absorb a significant amount of water, which then percolates downward under the influence of gravity, thus increasing the SWC. These results were consistent with previous studies[30] that had shown a more significantly influence on soil moisture characteristics through the combination of no-tillage and straw mulching. During the pod-setting and pod-filling stage, soybean was in its peak growth season and relies on water primarily from the deeper soil layers where the main root system was located. Therefore, there were no significant differences (p>0.05) in SWC among the four treatments in the 35 cm soil layer. This was in line with the conclusion from previous research[30] that the tillage mode had no significant impact on SWC in the deep soil layers. The experimental results also showed a significantly increase by an average of 3.94% to 10.24% in ST in the 25-35 cm soil layers for the NTS and NTSM treatments compared to the PTS and CTS treatments. This could be attributed to the reduced energy exchange between the soil and atmosphere after the uniform straw mulching in the NTS and NTSM treatments, leading to a significant increase in soil temperature. Additionally, the moist and warm environment promoted the decomposition of straw mulch, which generated heat and increases the heat release from the soil[31]. These findings aligned with the perspective presented in literature[32] that straw mulching can enhance soil temperature by reducing diurnal temperature variations. In conclusion, the NTS and NTSM treatments demonstrated significant soil insulation and moisture retention effects compared to the PTS and CTS treatments, making them to be the important mechanized sowing and planting patterns for effectively regulating soil water and thermal characteristics.

4.1.2 Influence of mechanized sowing and cultivation modes on soil physical structure

Soil physical structure referred to the overall properties that reflect the types, quantity, and pore conditions of soil aggregates, and it was commonly characterized by the indicators such as SBD, STP, and STPR.

As a result of natural sedimentation of soil particles, the soil became more compact and less permeable with increasing depth[33]. Therefore, under the experimental conditions, SBD and solid and liquid phase ratios of soil significantly increased (p<0.05), while STP and soil gas phase ratio significantly decreased with the increasing depth (Table 2 and Figure 5). The findings above were consistent with the findings from previous studies[18]. The experimental results showed that the PTS and CTS treatments achieved the near-ideal STPR in the 5 cm, 15 cm, and 25 cm soil layers, while the NTS and NTSM treatments achieved the near-ideal STPR in the 5 cm soil layer. This was mainly because the tillage operation in the PTS and CTS treatments can optimize STPR in the plowed layer, while the NTS and NTSM treatments only disturbed the soil during the sowing operation, without significantly affecting STPR in the deeper soil layers[33]. These findings were similar to the conclusions drawn in previous studies[34], which suggested that tillage practices could improve STPR and physical structure.

In the experimental year, compared to the PTS and CTS treatments, the SBD of NTS and NTSM treatments showed a significantly increased by an average of 2.98% to 6.27%, and the STP of NTS and NTSM treatments showed a significantly decreased by an average of 3.88% to 6.53% in the 5-25 cm soil layers (Table 2). The results above were mainly because the PTS and CTS treatments can loosen the soil and increase soil porosity, while crop residued with high cellulose content mixed with soil reduces soil bulk density[34]. On the other hand, the NTS and NTSM treatments for undisturbed soil resulted in a more compact arrangement of soil particles due to natural settling[18]. The results were consistent with the findings in previous studies[35], showing that reduced or no-tillage practices may increase SBD and decrease STP. There were no significant differences (p>0.05) in SBD and STP among the four mechanized sowing and cultivation modes in the 35 cm soil layer. This might be attributed to the fact that the operational depth of all four treatments did not reach 35 cm, resulting in insignificant effects on SBD and STP in this soil layer. The finding aligned with the conclusion of previous studies[4] that tillage practices had no impact on SBD and porosity in deeper soil layers.

The experimental results indicated that there were minimal differences in the solid-phase and liquid-phase ratios of soil among the four sowing and cultivation modes across different soil layers. However, the soil gas phase ratio of PTS and CTS treatments showed a significantly increase by an average of 8.26% to 25.97% in the 15-25 cm soil layers compared to the NTS and NTSM treatments (Figure 5), leading to a nearly ideal state of STPR for the PTS and CTS treatments in the 15 cm and 25 cm soil layers (Table 3). These results aligned with the findings of previous studies[10] that tillage practices such as plough tillage and rotary tillage could improve the three-phase ratios and physical structure of the plow soil layer. Similarly, since none of the four mechanized sowing and cultivation modes were operated below 35 cm soil depth, there were no significant differences in GSSI in the 35 cm soil layer among the treatments, resulting in similar STPR of the 35 cm soil layer. This was consistent with the conclusion from a literature[8] showing that tillage practices have no significant impact on the STPR of deep soil layers.

4.2 Influence of mechanized tillage and sowing modes on soybean yield and economic benefits

Suitable cultivation practices could also promote the improvement of crop yield and economic benefits. Under the experimental conditions, the soybean yield in 2020 for the same treatments was lower than that in 2021. The result was mainly attributed to the fact that soybeans require a water supply of 500-600 mm/a[36], while the average annual rainfall in the experimental area in 2020 was 750 mm, exceeding the maximum water demand by 25%, which was unfavorable for soybean growth. The finding above was consistent with the research results from the literature[37] indicating that there was a reduction in crop yield during the years with excessive rainfall.

In 2020 (with an average rainfall of 750 mm), the PTS and CTS treatments had higher soybean yield than NTS and NTSM treatments. This could be attributed to the fact that the PTS and CTS treatments result in a higher soil water loss compared to the NTS and NTSM treatments[11], soil water content of PTS and CTS treatments were suitable for the crop growth with excessive rainfall in years, leading to relatively higher crop yields. The finding aligned with the conclusion from literature[10] that in years with abundant water supply, conventional tillage practices result in significantly higher crop yields compared to no-tillage. Compared with PTS and CTS treatment, the soybean yield of NTS treatment significantly decreased, but the NTS treatment reduced the autumn agricultural machinery preparation projects, greatly reduced the input of agricultural machinery and manpower, and made the annual benefits of PTS, CTS and NTS treatments similar. NTSM treatment was not significant different with PTS and CTS, and reduced stubble crushing operations compared with NTS treatment, so the annual profit was higher than the PTS, CTS and NTS treatments.

In 2021 (with an average rainfall of 600 mm), the PTS and CTS treatments had lower soybean yield than NTS and NTSM treatments, which attributed to the NTS and NTSM treatments could promote soil conservation and moisture retention (Figure 3 and Figure 4), and provided favorable conditions for significant yield improvement in normal rainfall years for soybean cultivation. The finding above was consistent with the findings from the literature[38] that in years with average or below-average rainfall, no-tillage or conservation tillage practices result in higher crop yields compared to conventional tillage. And the soybean yield of PTS and CTS treatments were significantly lower than that of NTSM treatment, meanwhile the NTSM treatment with lower mechanical operation cost leading to a more obvious economic benefit advantage.

5 Conclusions

Based on the findings from the 2-year-repeat experiments, during the pod-setting and pod-filling period of soybean, the NTS and NTSM treatments exhibited better effects on deep soil insulation and shallow soil moisture retention, SWC showed a significantly increase by 2.35% to 7.98% in the 5-15 cm soil layer and ST showed a significantly increased by 3.94% to 10.42% in the 25-35 cm soil layer than PTS and CTS treatments. The PTS and CTS treatments could improve the soil physical structure, especially significantly improved the soil three ratio in 15-25 cm soil layer. Compared with PTS and CTS treatments, NTS and NTSM treatments significantly increased SBD by 2.98% to 6.72% and significantly reduced STP by 3.88% to 6.53% in the 5-25 cm soil layer, and significantly reduced soil gas phase ratio by 8.26% to 6.27% at the 15-25 cm soil layers. The NTSM treatment was not significantly lower than other treatments in the soybean yield, meanwhile, the average annual profit per unit area of NTSM treatment increased by 12.84%, 12.41% and 8.57% compared with PTS, CTS and NTS, respectively. Therefore, it was recommended to implement a maize-soybean rotation system that combines no-tillage with straw mulching and other tillage practices in the maize-soybean rotation zone, providing important support for the conservation of mollisols.

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