

Original Research

Different Soil Tillage Methods on Soil Capacity and Maize Yield in Hulunbuir Area

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Abstract

Conventional tillage is the most common practice in the Hulunbuir region; however, it may harm the soil's physical properties. Reasonable tillage methods can improve soil physical and chemical properties and create a good soil environment for crop growth. The objective of this study is to analyze the effects of 10 sets of tillage methods on soil capacity, soil moisture, agronomic characteristics, and the yield of spring maize (*Zea mays* L.) fields. The results derived indicate a reduction in soil bulk density under tillage methods T2, T3, T4, T7, and T8. While the effect of individual tillage methods on specific agronomic characteristics of maize was minimal, variations in tillage practices did significantly affect the mechanical harvesting attributes of the crop. Specifically, the combined treatments of T6 × N2 and T8 × N2 demonstrated a higher net income per hectare across both the 2019 and 2020 growing seasons. The experimental findings evidently demonstrate the effectiveness of two specific tillage methods for implementation in the Hulunbuir region: T6 × N2 (deep rotation with stubble clearing and straw returning) and T8 × N2 (deep tillage combined with comprehensive straw crushing and returning). These practices were beneficial in their capacity to augment soil organic matter content while simultaneously enhancing the stability of soil aggregates.

Keywords: tillage methods, soil bulk density, soil moisture, agronomic characteristics, maize yield

Introduction

Corn (*Zea mays* L.) is the most extensively cultivated food crop in China, playing a crucial role in ensuring

the national food security. In 2020, China produced 38.9% of its total food from corn. The Inner Mongolia Autonomous Region, a significant corn-growing area, has witnessed an expansion in its maize cultivation to 3.82 million hectares, yielding 27.42 million tons and securing the third rank in national production. Hulunbuir City, located in this region, is a prominent maize-producing locality. The Hulunbuir region is

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blessed with abundant sunlight and rainfall, alongside pronounced monsoon climate traits, which collectively create ideal conditions for agricultural development.

In contrast to other major corn-producing regions in China, the Hulunbuir area employs a comparatively basic and outdated approach to farming. The local climatic conditions and the agricultural practices of farmers in Hulunbuir city predominantly involve 2 primary methods of cultivation: shallow plowing and no-till farming, especially for spring maize. However, these prevailing cultivation methods in the principal corn-producing zones have resulted in shallow plowing depths, significant soil compaction, reduced capacity for soil to store and retain water, and increased resistance to root growth. Traditional farming practices often involve heavy machinery, which compacts the soil further, creating hardpans and a reduction in the effective soil volume available for cultivation. This exacerbates water scarcity in the soil. Such inefficient farming methods have become a key obstacle to enhancing and stabilizing crop yields. Soil cultivation is a vital aspect of maize production. Various tillage methods affect soil hardness, soil properties, and maize yield. Effective tillage methods are essential for optimizing soil moisture retention, nutrient fixation, and boosting crop yields.

The application of appropriate tillage methods in crop cultivation plays a crucial role in plant growth by influencing the composition of the soil environment [1, 2]. Dalal and Chan [3] reported that cultivation and cropping significantly affect the amounts of soil organic matter, while several studies also have found substantial effects of different tillage methods on topsoil environment, which in turn affects maize yield [4, 5].

In addition, crop residues are a vital asset for sustainable agricultural productivity. The practice of returning straw to the field not only mitigates environmental pollution from straw burning but also positively affects soil fertility [6]. Integrating effective tillage management with straw return bolstered the effect on maintaining or restoring organic matter [7]. Leaving straw on the fields can also enhance soil structure, carbon, and nitrogen contents [8]. Currently, many farmers in Hulunbuir customarily burn corn straw post-harvest, leading to environmental pollution and resource wastage. Therefore, reasonable application of corn straw not only fosters sustainable soil fertility in the region but can also enhance farmers' income to a certain degree.

In the Hulunbuir region, there has been limited research on combining tillage methods with straw return. This gap has led agricultural experts in Hulunbuir to intensify their studies on tillage technologies in recent years. Their objective is to address the challenges faced in corn production in the area. Based on existing research and local conditions, We hypothesize that the implementation of deep rotation or deep tillage combined with straw returning will significantly enhance maize yield in the Hulunbuir region through 2 synergistic mechanisms: (1) Deep plowing rotation

or deep tillage contributes to the reduction of soil bulk density [9], thus improve the soil structural stability; (2) The integration of deep rotation or deep tillage with straw incorporation leads to an increase in soil water content [10]. This hypothesis, if proven, could provide valuable insights into optimizing agricultural production in the Hulunbuir region and potentially offer a reference for similar regions. This research involved an analysis of 10 different tillage methods. These methods included farmers' shallow rotation, deep rotation, subsoiling, deep tillage, no-tillage, and various tillage methods involving straw return, such as stubble-shoving, ridge-cleaning and deep rotation with straw returning, subsoiling with straw crushing total returning to the field, deep tillage with straw crushing total returning to the field, no-tillage with straw crushing total returning to the field, alongside a typical local straw returning approach.

The study aimed to evaluate the effect of these methods on soil capacity, soil moisture, agronomic characteristics, and the yield of spring maize fields. The purpose of this research was to develop and refine a cultivation technology model that is tailored to the region's primary maize varieties. It sought to provide a theoretical foundation for selecting appropriate tillage methods for spring maize fields in Hulunbuir City.

Materials and Methods

The test maize (*Zea mays* L.) was Demeiya 1. This study took place between 2019 and 2020 at the experimental site of Zhonghe Town, belonging to the Hulunbuir Institute of Agricultural and Animal Husbandry Science in the Inner Mongolia Autonomous Region (coordinates 47°40', 122°36'). This region experiences average annual sunshine duration between 2,600 and 2,800 h, average annual accumulated temperature ranging from 2,100 to 2,350°C, and average annual rainfall between 450 and 530 mm. Specifically, during the maize growing season, the rainfall varied from 320 to 380 mm, the accumulated temperature during the reproductive period was 2,250°C, and the sunshine hours during this period totaled 1,380 h. The soil at the test site, previously utilized for maize cultivation, was characterized as dark brown loam.

This experiment incorporated ten technical models. These included shallow rotation and no-tillage control methods practiced by farmers (T1, T5), 3 deep tillage methods (T2, T3, T4, T6), and five straw return methods (T6, T7, T8, T9, T10) (Table 1). Additionally, three levels of nitrogen fertilizer application were tested: 0 kg/mu, 15 kg/mu, and 20 kg/mu. Each method was applied over a large area for comparative analysis. The experiment featured 3 replications for each treatment, resulting in a total of 30 plots, with each plot covering an area of 45 m². The rototiller reached a depth of 10-12 cm, while the deep tillage and subsoiling methods reached 28-30 cm. The quantity of straw returned was 6000kg/hm². All straw was integrated into the soil using a spade

Table 1. Design of split-zone experiment of tillage method and fertilizer application.

Tillage method treatment		Fertilizer application test	
		Fertilizer application	
T1	Farmers' shallow rotation	N1	No fertilizer application
T1		N3	Apply pure N 300 kg/ha
T1		N2	Apply pure N 225 kg/ha
T2	Deep rotation (25-30 cm)	N2	225 kg/ha of pure N
T3	Subsoiling (30-40 cm)	N2	225 kg/ha of pure N
T4	Deep tillage (30-40 cm)	N2	225 kg/ha of pure N
T5	No-tillage	N2	225 kg/ha of pure N
T6	Stubble-shoving, ridge-cleaning and deep rotation with straw returning	N2	225 kg/ha of pure N
T7	Subsoiling with straw crushing total returning to the field	N2	225 kg/ha of pure N
T8	Deep tillage with straw crushing total returning to the field	N2	225 kg/ha of pure N
T9	No-tillage with straw crushing total returning to the field	N2	225 kg/ha of pure N
T10	Typical local straw returning pattern	N2	225 kg/ha of pure N

plow to ensure thorough mixing of the upper and lower layers. Thereafter, the ground was harrowed, and the straws were buried to a depth of 30 cm. All straw return processes were completed in autumn, prior to irrigation.

Soil samples were collected annually, both at the beginning of the year and during the harvest periods, for the purpose of determining the soil's bulk density and its water content.

Soil Bulk Density: We collected soil samples from depths of 0-20 cm, 20-40 cm, and 40-60 cm in the spaces between maize rows at each experimental site during both the sowing and harvesting phases. A ring knife was utilized for this purpose. This procedure was conducted in triplicate for each treatment. Post-collection, the samples were dried to measure their bulk density.

Soil Water Content: To determine the soil water content, we probed 1 m of soil using a soil auger at before sowing (BS), large trumpet (V12), silking (R1), and after harvest (AH) stages. The soil profile was divided into three layers: 0-20 cm, 20-40 cm, and 40-60 cm. Each of these layers was analyzed in triplicate for each treatment. Soil samples were collected in aluminum boxes. The weight of the moist soil (including the aluminum box's weight) was immediately recorded. Thereafter, these samples were oven-dried at 105°C for 24 h, after which the dry soil weight (including the box's weight) was noted.

$$\text{Soil moisture content (\%)} = (\text{wet soil weight} - \text{dry soil weight}) / (\text{dry soil weight} - \text{aluminum box weight}) \times 100\%$$

Lodging Rate: At the end of the milk ripening stage, the lodging rate was calculated as the proportion of

plants with a tilt exceeding 45 degrees (yet not broken) relative to the total plant count in the experimental plot.

Percentage of shattering: 3 to 5 sample points were chosen, with each point representing a 2-m-long section including 4 to 6 rows of maize. At these points, both the fallen ears of maize and any loose grains were collected. The weight of these dropped ears and grains per unit area was then measured to calculate the rate of yield loss.

$$\text{Percentage of shattering \%} = \text{unit area drop grain weight} / \text{unit area yield} \times 100$$

Grain broken rate: To determine the rate of grain breakage, a process was implemented involving the collection of 2 kg of seed samples directly from the harvester bin. The moisture content of these samples was promptly measured. This was followed by a manual sorting process to separate intact grains, broken grains, and impurities, each category being weighed individually. The rate of grain breakage was then calculated by weight.

$$\text{grain broken rate \%} = \text{weight of broken seeds} / \text{weight of seed samples} \times 100$$

Statistical Analysis

The analysis of the experimental data was conducted using Excel 2016, DPS 7.05, and SPSS 23.0 statistical software. Excel 2016 and SPSS 23.0 were used to draw all the figures and tables. The "ANOVA" function of DPS 7.05 was performed to test the effects of tillage methods on soil bulk density and agronomic traits of maize. Differences between treatments were identified

Table 2. Effects of soil tillage and fertilization on soil bulk density.

Tillage methods	Fertilizer application	Sowing time in 2019		Sowing time in 2020		Sowing time in 2019		Sowing time in 2020		Sowing time in 2019	Sowing time in 2020	`	`
		0-20 cm		20-40 cm		20-40 cm		40-60 cm					
T1	N1	1.14±0.02a	1.08±0.01cd	1.11	1.33±0.03bcde	1.29	1.24±0.02de	1.29	1.46±0.02d	1.35±0.02b	1.41		1.41
T1	N2	1.16±0.03a	1.05±0.02cd	1.11	1.34±0.02bcd	1.34	1.33±0.04abc	1.34	1.47±0.01cd	1.40±0.03b	1.44		1.44
T1	N3	1.15±0.02a	1.06±0.01cd	1.11	1.31±0.03def	1.29	1.26±0.02cd	1.29	1.45±0.03d	1.36±0.04b	1.41		1.41
T2	N2	1.07±0.04cd	1.15±0.01b	1.11	1.30±0.02ef	1.28	1.26±0.03cd	1.28	1.40±0.02f	1.38±0.02b	1.39		1.39
T3	N2	1.11±0.01abc	1.00±0.05e	1.06	1.35±0.02bc	1.31	1.26±0.03cd	1.31	1.51±0.02b	1.35±0.02b	1.43		1.43
T4	N2	1.12±0.04ab	1.05±0.01cd	1.09	1.28±0.01f	1.24	1.19±0.08ef	1.24	1.41±0.02ef	1.35±0.04b	1.38		1.38
T5	N2	1.15±0.01a	1.18±0.02ab	1.17	1.39±0.01a	1.38	1.37±0.02a	1.38	1.58±0.02a	1.46±0.01a	1.52		1.52
T6	N2	1.08±0.02bc	1.14±0.03b	1.11	1.36±0.02ab	1.30	1.23±0.02def	1.30	1.50±0.01bc	1.35±0.01b	1.43		1.43
T7	N2	1.12±0.03ab	1.07±0.02cd	1.10	1.33±0.03bcde	1.25	1.17±0.05f	1.25	1.56±0.05a	1.30±0.03c	1.43		1.43
T8	N2	1.03±0.03d	1.04±0.02de	1.04	1.18±0.02g	1.18	1.17±0.05ef	1.18	1.41±0.01ef	1.48±0.04a	1.44		1.44
T9	N2	1.15±0.01a	1.23±0.04a	1.19	1.31±0.01de	1.33	1.34±0.02ab	1.33	1.56±0.02a	1.49±0.02a	1.53		1.53
T10	N2	1.11±0.01abc	1.09±0.01c	1.10	1.32±0.01cde	1.31	1.29±0.01bcd	1.31	1.44±0.01de	1.46±0.04a	1.45		1.45

Note: Within each soil layer, means in the same column followed by the same letters are not significantly different at $P < 0.05$ (least significance difference (LSD) test), farmers' shallow rotation (T1), deep rotation (25-30 cm) (T2), subsoiling (30-40 cm) (T3), deep tillage (30-40 cm) (T4), no-tillage (T5), stubble-shoving, ridge-cleaning and deep rotation with straw returning (T6), subsoiling with straw crushing total returning to the field (T7), deep tillage with straw crushing total returning to the field (T8), no-tillage with straw crushing total returning to the field (T9), typical local straw returning pattern (T10), no fertilizer application (N1), apply pure N 225 kg/ha (N2), apply pure N 300 kg/ha (N3).

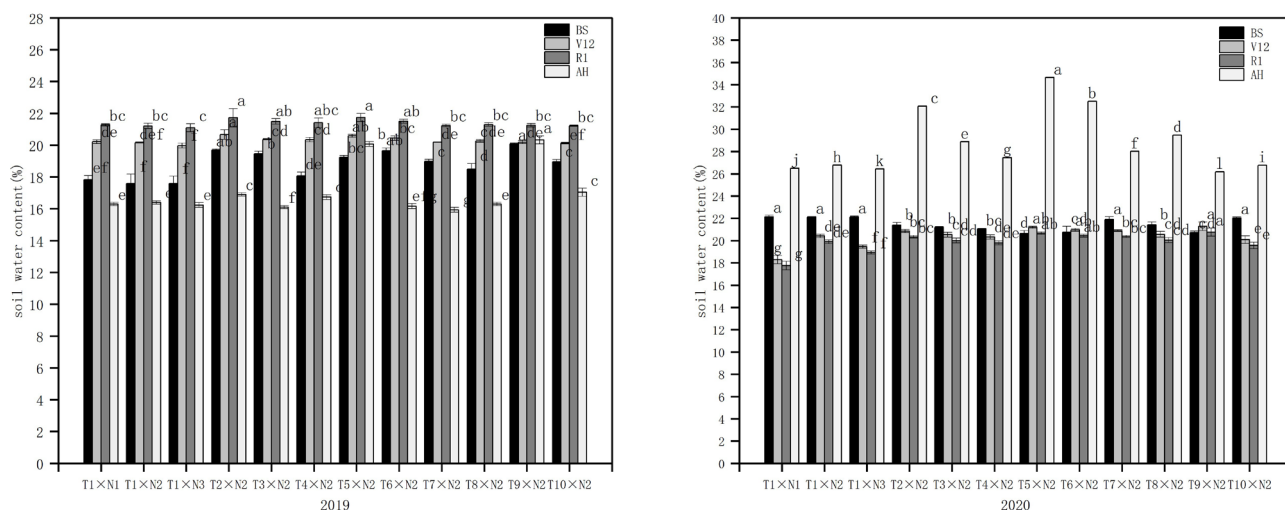


Fig. 1. Changes of 0-20 cm soil water content in different years.

Note: Within the same year, values followed by different letters in the same column are significantly different at 5% significance level; Farmers' shallow rotation (T1), deep rotation (25-30 cm) (T2), subsoiling (30-40 cm) (T3), deep tillage (30-40 cm) (T4), no-tillage (T5), stubble-shoving, ridge-cleaning and deep rotation with straw returning (T6), subsoiling with straw crushing total returning to the field (T7), deep tillage with straw crushing total returning to the field (T8), no-tillage with straw crushing total returning to the field (T9), typical local straw returning pattern (T10), no fertilizer application (N1), apply pure N 225 kg/ha (N2), apply pure N 300 kg/ha (N3); BS = before sowing, V12 = big flare period, R1 = silking period, AH = after harvest.

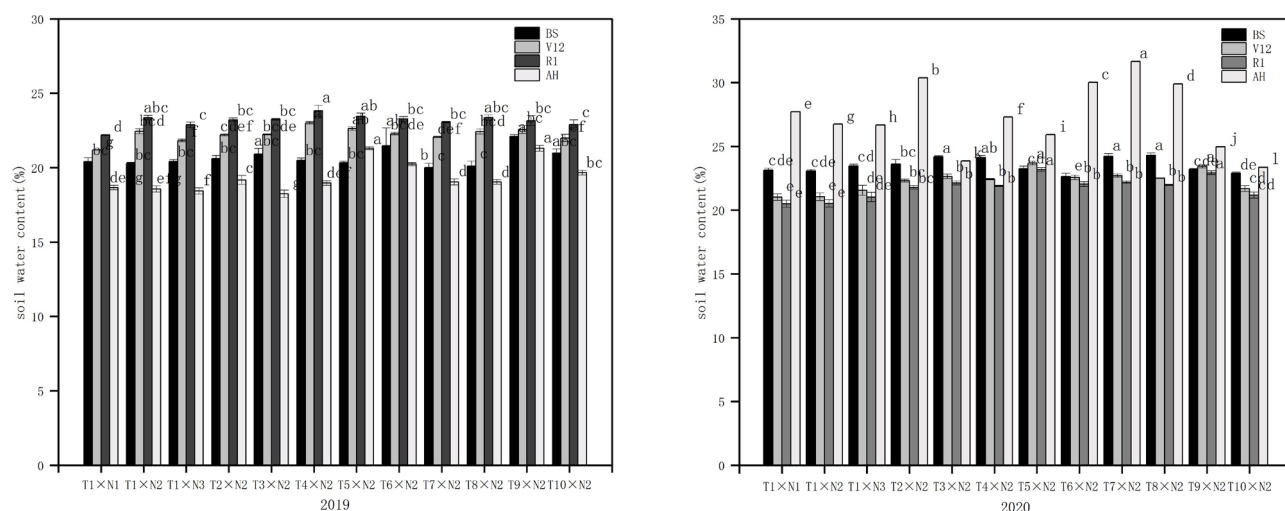


Fig. 2. Changes of soil water content in 20-40 cm in different years.

Note: Within the same year, values followed by different letters in the same column are significantly different at 5% significance level; Farmers' shallow rotation (T1), deep rotation (25-30 cm) (T2), subsoiling (30-40 cm) (T3), deep tillage (30-40 cm) (T4), no-tillage (T5), stubble-shoving, ridge-cleaning and deep rotation with straw returning (T6), subsoiling with straw crushing total returning to the field (T7), deep tillage with straw crushing total returning to the field (T8), no-tillage with straw crushing total returning to the field (T9), typical local straw returning pattern (T10), no fertilizer application (N1), apply pure N 225 kg/ha (N2), apply pure N 300 kg/ha (N3); BS = before sowing, V12 = big flare period, R1 = silking period, AH = after harvest.

using the least significant difference (LSD) at the $P < 0.05$ level.

Results and Discussion

Soil Bulk Density

The data presented in Table 2 reveal significant differences in soil bulk density across various soil

layers during the sowing phase of 2019 and 2020. These differences were observed under varying tillage methods and nitrogen application rates. Notably, in comparison with the control groups (T1 and T5), the soil bulk density in the 0-20 cm, 20-40 cm, and 40-60 cm layers was found to be lower in other tillage methods during the sowing period. Wang et al. [11] reported similar results, finding that soil disturbances resulting from plowing and straw returning led to decreased soil bulk density compared to no-tillage soil. In comparison

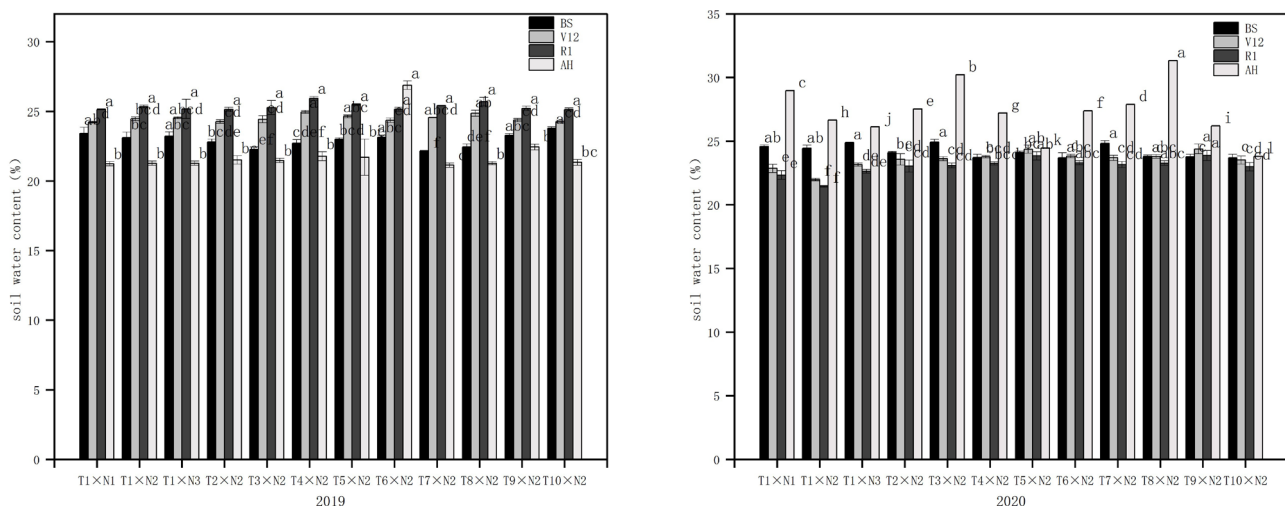


Fig. 3. Changes of soil water content in 40-60 cm in different years.

Note: Within the same year, values followed by different letters in the same column are significantly different at 5% significance level; Farmers' shallow rotation (T1), deep rotation (25-30 cm) (T2), subsoiling (30-40 cm) (T3), deep tillage (30-40 cm) (T4), no-tillage (T5), stubble-shoving, ridge-cleaning and deep rotation with straw returning (T6), subsoiling with straw crushing total returning to the field (T7), deep tillage with straw crushing total returning to the field (T8), no-tillage with straw crushing total returning to the field (T9), typical local straw returning pattern (T10), no fertilizer application (N1), apply pure N 225 kg/ha (N2), apply pure N 300 kg/ha (N3); BS = before sowing, V12 = big flare period, R1 = silking period, AH = after harvest.

to the control groups (T1, T5), the soil bulk density in the 0-20 cm layer during the sowing period for treatments T8 × N2, T3 × N2, and T4 × N2 was found to be lower. The average values over two years for these treatments were 1.04 g/cm³, 1.06 g/cm³, and 1.09 g/cm³, respectively. Prior research has demonstrated that deep or subsoil tillage with straw returning reduced the soil bulk density, while enhancing the content of organic carbon in the soil. Moreover, it increased soil microbial populations, soil enzyme activities, and grain yield [12, 13].

Soil Water Content

From Figs 1-3, it is evident that in 2019, the moisture levels in the soil layers measuring 0-20 cm, 20-40 cm, and 40-60 cm did not vary significantly across various growth stages and tillage methods. The moisture peaked during the silking stage, but notably decreased at the harvest stage. During the critical growth phases of maize (big flare period and silking stages), the moisture in the 0-20 cm soil layer under tillage treatments demonstrated little differences when compared to the control group. In contrast, in the deeper soil layers of 20-40 cm and 40-60 cm, moisture levels were notably higher under the T4 × N2, T8 × N2, and T9 × N2 treatments during the critical growth phases of maize both in 2019. In 2020, the soil water content across three different soil layers (0-20 cm, 20-40 cm, and 40-60 cm) revealed significant differences under different tillage conditions at various growth stages. Notably, after harvest, there was a significant increase in soil water content for each treatment. Specifically, in the 0-20 cm soil layer, the treatments T2 × N2, T6 × N2, and T8 × N2 exhibited higher soil water

content than the control T1, but lower than the control T5. In the 20-40 cm layer, the T7 × N2 and T2 × N2 treatments had higher soil water content. Meanwhile, in the 40-60 cm layer, the T8 × N2 and T3 × N2 treatments demonstrated higher soil water content after harvest compared to other tillage treatments. The findings of this study demonstrate that the implementation of deep rotational subsoiling with total straw return, as well as deep tillage with straw crushing and total return, led to a significant increase in soil water content. Wen et al. [14] reported that subsoiling with straw returning could enhance soil characteristics and stabilize the physical properties of the plow layer. Similarly, Li [15] observed that deep plowing methods significantly improve soil water content. In general, the moisture content for each treatment in 2020 exceeded that of 2019, indicating that different tillage treatments have variably improved soil moisture levels.

Agronomic Traits of Maize

Tables 3-4 revealed that in 2019, the plant height for T6 × N2 was lower, whereas the plant heights in other treatments surpassed that of T1 × N1, with no significant difference in plant height across treatments. The plant heights for T9 × N2 and T10 × N2 were higher, and each treatment, when compared to T5 × N2, displayed no significant differences. When contrasted with the control T5 × N2, the ear positions for T3 × N2 and T4 × N2 were situated lower, and the stems for T9 × N2 and T10 × N2 were slimmer. In contrast, relative to the control T1 × N1 in 2020, the plant height, ear position, and stem diameter in other tillage treatments were greater than those in T1 × N1. Specifically, T3 × N2, T6 × N2, and

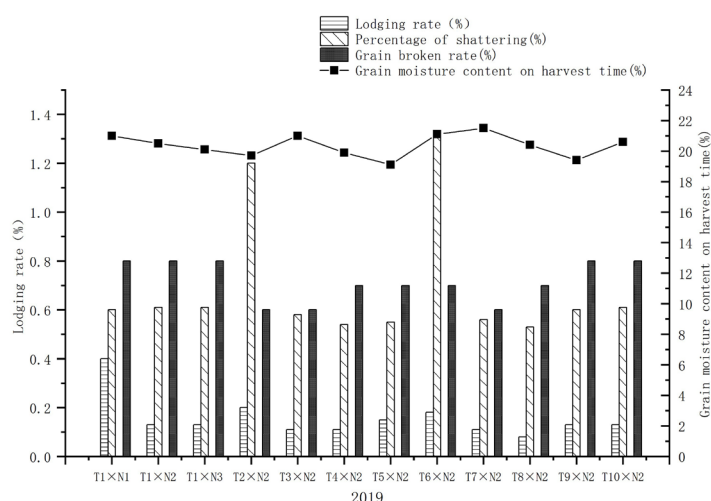


Fig. 4. Comparison of mechanical harvesting traits under different tillage methods (2019).

Note: Farmers' shallow rotation (T1), deep rotation (25-30 cm) (T2), subsoiling (30-40 cm) (T3), deep tillage (30-40 cm) (T4), no-tillage (T5), stubble-shoving, ridge-cleaning and deep rotation with straw returning (T6), subsoiling with straw crushing total returning to the field (T7), deep tillage with straw crushing total returning to the field (T8), no-tillage with straw crushing total returning to the field (T9), typical local straw returning pattern (T10), no fertilizer application (N1), apply pure N 225 kg/ha (N2), apply pure N 300 kg/ha (N3).

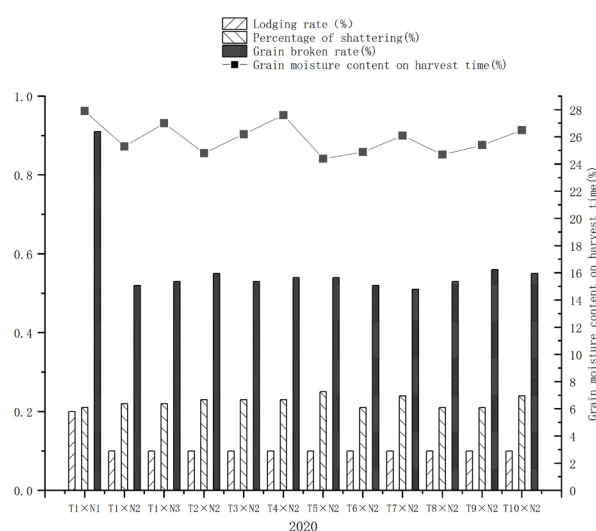


Fig. 5. Comparison of mechanical harvesting traits under different tillage methods (2020).

Note: Farmers' shallow rotation (T1), deep rotation (25-30 cm) (T2), subsoiling (30-40 cm) (T3), deep tillage (30-40 cm) (T4), no-tillage (T5), stubble-shoving, ridge-cleaning and deep rotation with straw returning (T6), subsoiling with straw crushing total returning to the field (T7), deep tillage with straw crushing total returning to the field (T8), no-tillage with straw crushing total returning to the field (T9), typical local straw returning pattern (T10), no fertilizer application (N1), apply pure N 225 kg/ha (N2), apply pure N 300 kg/ha (N3).

T9 × N2 demonstrated increased plant heights, the ear position for T8 × N2 was lower, and the stem diameter demonstrated no significant difference ($P < 0.05$) under the same fertilization rates. Compared to T5 × N2, the agronomic traits exhibited no remarkable differences. These results indicate that the agronomic characteristics of T1 × N1 were inferior, attributed to the fertilization rate of 0 kg/mu. Under identical fertilization rates, when contrasted with the control T5 × N2, various tillage treatments had minimal effect on the agronomic characteristics of maize. However, in comparison with

the control T1 × N1, the plant height and ear position in each treatment were superior to those in T1 × N1.

Mechanical Harvest Traits

The correlation coefficient of grain moisture content on harvest time and lodging rate is 0.686, $P < 0.05$. Lodging rate is extremely significantly correlated to grain broken rate (0.824, $P < 0.01$) (Table 5). High grain moisture content at harvest time could probably result in a high lodging rate. Furthermore, a high lodging rate can lead to an increase in grain breakage. Figs 4-5

Table 3. Effects of soil tillage and fertilization on agronomic traits of maize in 2019.

Tillage methods and Fertilizer application	Height (cm)	Ear position (cm)	Stem diameter (mm)
T1×N1	224.00b	80.00c	2.43a
T1×N2	306.67a	114.33a	2.40a
T1×N3	283.33a	92.67bc	2.37a
T2×N2	290.33a	91.00bc	2.30a
T3×N2	287.00a	85.00c	2.30a
T4×N2	293.67a	86.67c	2.27ab
T5×N2	308.33a	114.67a	2.27ab
T6×N2	228.33b	108.00ab	2.27ab
T7×N2	291.67a	94.67abc	2.27ab
T8×N2	294.67a	114.33a	2.27ab
T9×N2	302.00a	98.33abc	2.03c
T10×N2	307.67a	108.67ab	1.80d

Note: Within each factor, means in the same column followed by the same letters are not significantly different at $P < 0.05$ (least significance difference (*LSD*) test); farmers' shallow rotation (T1), deep rotation (25-30 cm) (T2), subsoiling (30-40 cm) (T3), deep tillage (30-40 cm) (T4), no-tillage (T5), stubble-shoving, ridge-cleaning and deep rotation with straw returning (T6), subsoiling with straw crushing total returning to the field (T7), deep tillage with straw crushing total returning to the field (T8), no-tillage with straw crushing total returning to the field (T9), typical local straw returning pattern (T10), no fertilizer application (N1), apply pure N 225 kg/ha (N2), apply pure N 300 kg/ha (N3).

Table 4. Effects of soil tillage and fertilization on agronomic traits of maize in 2020.

Tillage methods and Fertilizer application	Height (cm)	Ear position (cm)	Stem diameter (mm)
T1×N1	276.67d	96.67c	1.93b
T1×N2	290.00cd	104.00abc	2.57a
T1×N3	290.00cd	98.00c	2.40ab
T2×N2	300.00abc	103.00abc	2.43ab
T3×N2	313.33a	109.33abc	2.27ab
T4×N2	306.67ab	117.33abc	2.30ab
T5×N2	300.00abc	127.33ab	2.27ab
T6×N2	313.33a	122.00abc	2.40ab
T7×N2	296.67bc	113.00abc	2.43ab
T8×N2	303.33abc	100.67bc	2.40ab
T9×N2	313.33a	128.00a	2.27ab
T10×N2	296.67bc	126.33ab	2.13ab

Note: Within each factor, means in the same column followed by the same letters are not significantly different at $P < 0.05$ (least significance difference (*LSD*) test); farmers' shallow rotation (T1), deep rotation (25-30 cm) (T2), subsoiling (30-40 cm) (T3), deep tillage (30-40 cm) (T4), no-tillage (T5), stubble-shoving, ridge-cleaning and deep rotation with straw returning (T6), subsoiling with straw crushing total returning to the field (T7), deep tillage with straw crushing total returning to the field (T8), no-tillage with straw crushing total returning to the field (T9), typical local straw returning pattern (T10), no fertilizer application (N1), apply pure N 225 kg/ha (N2), apply pure N 300 kg/ha (N3).

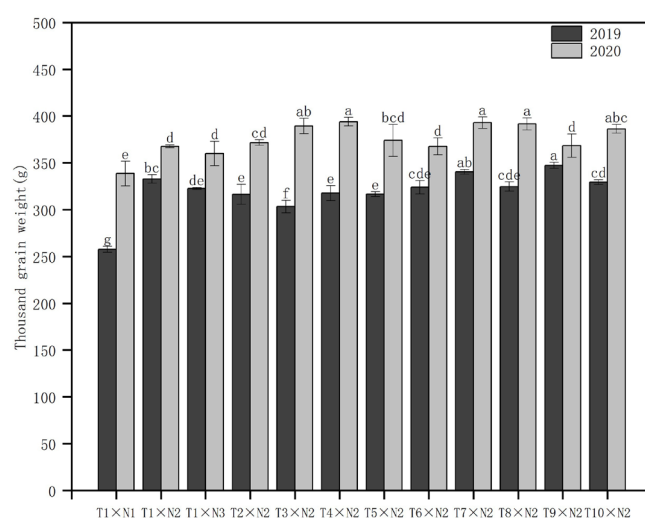


Fig. 6. Comparison of 1000-grain weight of different tillage methods in different years.

Note: Within the same year, values followed by different letters in the same column are significantly different at 5% significance level; farmers' shallow rotation (T1), deep rotation (25-30 cm) (T2), subsoiling (30-40 cm) (T3), deep tillage (30-40 cm) (T4), no-tillage (T5), stubble-shoving, ridge-cleaning and deep rotation with straw returning (T6), subsoiling with straw crushing total returning to the field (T7), deep tillage with straw crushing total returning to the field (T8), no-tillage with straw crushing total returning to the field (T9), typical local straw returning pattern (T10), no fertilizer application (N1), apply pure N 225 kg/ha (N2), apply pure N 300 kg/ha (N3).

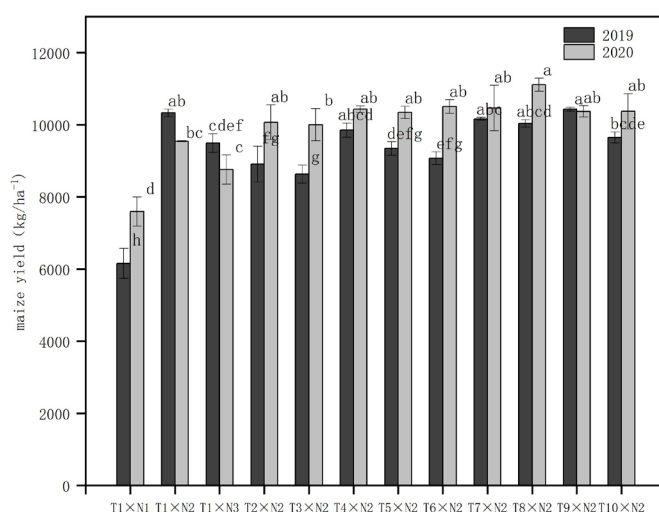


Fig. 7. Comparison of maize yield under different tillage methods in different years.

Note: Within the same year, values followed by different letters in the same column are significantly different at 5% significance level; Farmers' shallow rotation (T1), deep rotation (25-30 cm) (T2), subsoiling (30-40 cm) (T3), deep tillage (30-40 cm) (T4), no-tillage (T5), stubble-shoving, ridge-cleaning and deep rotation with straw returning (T6), subsoiling with straw crushing total returning to the field (T7), deep tillage with straw crushing total returning to the field (T8), no-tillage with straw crushing total returning to the field (T9), typical local straw returning pattern (T10), no fertilizer application (N1), apply pure N 225 kg/ha (N2), apply pure N 300 kg/ha (N3).

reveal that in 2019, the water content in the grains of all tillage treatments remained below 22% at harvest time, exhibiting minimal variation. However, certain treatments experienced higher rates of grain breakage. Notably, the grain broken rates in T3 × N2, T7 × N2, and T8 × N2 were comparatively lower than those observed in T1 × N1, T1 × N2, T1 × N3, and T5 × N2. In 2020, the moisture content in the grains at harvest for each tillage treatment surpassed the levels recorded in 2019, leading to a corresponding increase in grain broken rates. Among these, the moisture content in the grains of T2 ×

N2, T6 × N2, and T8 × N2 was less than that found in the control groups T1 × N1, T1 × N2, and T1 × N3, though the difference was not markedly significant compared to the control T5 × N2. Additionally, the 3 aforementioned treatments demonstrated relatively low rates of lodging, shattering, and grain breakage, suggesting these tillage methods were more effective than the others.

From Fig. 6, the 1000-grain weight for the T9 × N2 and T7 × N2 treatments exceeded that of the control, with significant differences noted in comparison to other treatments in 2019. In 2020, the 1000-grain weight under

Table 5. Correlation analysis of mechanical harvest traits under different tillage methods.

Index	Grain moisture content at harvest time (%)	Lodging rate (%)	Percentage of shattering (%)	Grain broken rate (%)
Grain moisture content at harvest time (%)	1			
Lodging rate (%)	0.686*	1		
Percentage of shattering (%)	-0.073	-0.383	1	
Grain broken rate (%)	0.532	0.824**	-0.334	1

Note: * and ** mean significant correlation at $P < 0.05$ and extremely significant correlation at $P < 0.01$, respectively.

the $T3 \times N2$, $T4 \times N2$, $T7 \times N2$, and $T8 \times N2$ treatments was higher, indicating a significant distinction from other treatments. However, no significant difference was observed among these four treatments. This indicates that the 1000-grain weight of maize was higher under deep loosening and deep tillage treatments.

Maize Yield

The data from 2019 and 2020 (Fig. 7) illustrate the maize yield of different tillage methods. The yield per hectare for various tillage treatments was lower than that of one of the control groups ($T1 \times N2$) in 2019. In 2020, the yield per hectare for various tillage treatments surpassed that of the control group ($T1 \times N1$, $T1 \times N2$, $T1 \times N3$). Notably, in certain instances, such as $T5 \times N2$, some treatments yielded lower than the control. Specifically, in 2019, the treatments $T8 \times N2$, $T7 \times N2$ and $T9 \times N2$ demonstrated higher yield per hectare, amounting to $10033.35 \text{ kg ha}^{-1}$, $10162.84 \text{ kg ha}^{-1}$ and $10429.42 \text{ kg ha}^{-1}$, respectively. In 2020, the treatments $T6 \times N2$ and $T8 \times N2$ outperformed others, recording yield of $10504.80 \text{ kg ha}^{-1}$ and $11107.61 \text{ kg ha}^{-1}$, respectively.

Discussion

The study revealed significant differences in soil bulk density across different soil layers, influenced by varying tillage methods and nitrogen application rates. In comparison to the control groups ($T1$, $T5$), the treatments $T2$, $T3$, $T4$, $T7$, and $T8$ demonstrated a decrease in soil bulk density across the 0-20 cm, 20-40 cm, and 40-60 cm soil layers. This suggests that tillage methods such as strip deep rotation, deep loosening, deep turning, and combined methods involving deep loosening or turning with full straw crushing and returning effectively break the plow pan, enhance soil permeability, and reduce soil bulk density. These findings align with the research of Zhao et al. [16], which indicated that straw return treatments lowered soil bulk density in the 0-20 cm and 20-40 cm layers. Additionally, research on Iranian sandy loam by Mosaddeghi et al. [17] found that soil bulk density and compaction lessened with increased tillage depth.

Subsoil tillage management practices also contribute to reducing soil bulk density [18, 19]. methods such as subsoiling at 35 cm (ST35) and 40 cm (ST40) have been demonstrated to effectively decrease soil bulk density and manage soil aggregate structure, particularly in the North China Plain [20].

In 2019, there were no significant differences in soil water content at depths of 0-20 cm, 20-40 cm, and 40-60 cm under various tillage methods during different growth stages. The peak in soil water content occurred during the silking stage, but notably declined at the harvest stage. Soil moisture at the 0-20 cm depth under tillage treatments demonstrated minimal difference from the control during critical maize growth stages (big flare period and silking period). However, at depths of 20-40 cm and 40-60 cm, soil moisture was higher under $T4 \times N2$ and $T8 \times N2$ treatments in 2020. Soil moisture content at 0-20 cm, 20-40 cm, and 40-60 cm depths under different tillage conditions did not vary significantly before sowing, during the big flare period, or at the silking period. However, a marked increase was observed during the harvest period. This suggests that deep plowing may enhance soil physical properties in deeper layers. In 2020, soil water content for each treatment was higher than in 2019, indicating varying levels of improvement due to different tillage treatments. Total straw deep tillage had a more pronounced effect on soil structure compared to conventional tillage, significantly reducing soil bulk density and increasing soil relative water content [21]. Guan et al. [22] and Peixoto et al. [23] demonstrated that subsoiling tillage reduced soil bulk density and increased soil porosity and water content in the mid-deep layer (20-120 cm). It was observed that subsoilers with lower wing mounting heights generally had higher soil moisture contents across various stages [24]. Studies by Wang et al. [25]; Zhao et al. [16] indicated that straw cover somewhat enhanced soil moisture at different depths. In addition, Zhang et al. [26] discovered that subsoiling increased soil water content at the 0-100 cm depth, particularly at V3 and V9 stages in dry years.

Comparing $T5 \times N2$ with other tillage treatments, we see minimal effect on maize's agronomic characteristics under identical fertilization conditions. However, when contrasted with the control group $T1 \times N1$, there were

significant differences in plant height, ear position, and stem diameter across the treatments. Specifically, $T9 \times N2$ and $T10 \times N2$ exhibited taller plants with slimmer stems, while the other treatments presented moderate measurements in these areas. Concerning mechanical harvesting characteristics, the two-year experiment results demonstrated that $T3 \times N2$ and $T8 \times N2$ had lower grain moisture content, rates of lodging, and grain breakage at harvest compared to control groups $T1 \times N1$, $T1 \times N2$, $T1 \times N3$, and $T5 \times N2$.

In terms of maize yield per hectare, in the specific conditions of $T7 \times N2$, $T8 \times N2$, and $T9 \times N2$ in 2019, the yield per hectare was notably higher. Each tillage treatment surpassed the control groups $T1 \times N1$, $T1 \times N2$, and $T1 \times N3$ in 2020. Some treatments, however, fell below the control $T5 \times N2$. Additionally, the $T6 \times N2$ and $T8 \times N2$ treatments in 2020 exceeded other tillage treatments in yield. Deep tillage effectively reduces subsoil compaction resulting from long-term conservation tillage practices, thereby enhancing crop productivity [27]. The practice of maize straw deep plowing and its integration into the soil demonstrated a significant yield-enhancing effect on maize [28]. This sustainable tillage practice effectively augments soil fertility, offering a valuable compensatory mechanism with significant theoretical implications [29].

Prior studies have demonstrated the positive effects of straw deep plowing on maize growth and yield improvement [30]. Specifically, deep tillage practices have recorded significantly higher grain yields compared to conventional tillage treatments [31]. Additionally, research conducted in Northeastern China has indicated a positive correlation between subsoil tillage and increased grain yields [32]. Sharma et al. [33] also reported that the integration of subsoiling and maize straw returning significantly enhances crop development and yield, primarily due to enhanced moisture conservation and warming effects during the late growth stages.

Conclusions

Based on the results of this study, the most effective tillage methods for adoption in the Hulunbuir region are $T6 \times N2$ (deep rotation with stubble clearing and straw returning) and $T8 \times N2$ (deep tillage combined with comprehensive straw crushing and returning). With these tillage approaches, $T6 \times N2$ and $T8 \times N2$, we observed that deep rotation or deep tillage with straw returning reduced the soil bulk density and enhanced soil water content compared with control methods practiced by farmers ($T1$, $T5$). In addition, these methods resulted in a reduced incidence of maize lodging and grain breakage, as well as reduced grain moisture content at the time of harvest. Additionally, these practices led to an increase in the weight of 1000 grains, thus promoting an increase in maize yield per hectare.

Over the long term, in practices involving deep tillage or subsoiling, there should be a greater emphasis on straw returning. This practice is beneficial as it increases soil organic matter and bolsters the stability of soil aggregates, as indicated in references [34, 35]. Moreover, the conclusions of this study hold significant implications for agricultural scientific research. The successful implementation of deep tillage and straw returning methods in the Hulunbuir region demonstrates the potential of these sustainable agricultural practices to enhance soil health and crop productivity in similar environments worldwide. This research contributes to the global understanding of sustainable agriculture and offers valuable insights for other regions facing similar challenges in maintaining soil health and crop productivity.

Conflict of Interest

The authors declare no conflict of interest.

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