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Effects of No-Tillage on Field Microclimate and Yield of Winter Wheat

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Abstract: Field studies were conducted in the North China Plain (NCP) during the 2023–2024 season to investigate the vertical microclimate, yield, and yield-related characteristics of winter wheat during the grain-filling stage under no-till direct seeding and conventional tillage. The aim was to compare the differences in microclimate between the two tillage methods in wheat fields and the impact of microclimate on yield. The results indicated that, compared to conventional tillage, no-till direct seeding reduced the air temperature and increased the relative humidity of the air at 20 cm and 100 cm above the ground during the wheat grain-filling period. The soil moisture content at 20 cm below the ground under no-till direct seeding was higher than under conventional tillage during the early grain-filling stage. Seven days before the wheat harvest, the dry weight per plant and the dry weight per spike were significantly greater under no-till direct seeding than under conventional tillage. Consequently, the thousand-grain weight of no-till direct seeding was significantly higher than that of conventional tillage, with an increase of 7.9%. The number of wheat sterile spikelets under no-till direct seeding was significantly lower than that under conventional tillage. Furthermore, the number of grains per spike was higher than that of conventional tillage. Although the number of harvested spikes under no-till direct seeding was 10.8% lower than under conventional tillage, the increase in thousand-grain weight and the number of grains per spike compensated for the reduced number of harvested spikes. As a result, the grain yield of winter wheat under no-till direct seeding was higher than that of conventional tillage, increasing by 2.7%. Therefore, adopting no-till direct seeding in the NCP is conducive to increasing winter wheat production and efficiency, as well as supporting sustainable agricultural development.

Keywords: winter wheat; no-tillage direct seeding; conventional tillage; air temperature; relative humidity of air; soil moisture content; yield

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Citation: Dong, Z.; Yang, S.; Li, S.; Fan, P.; Wu, J.; Liu, Y.; Wang, X.; Zhang, J.; Zhai, C. Effects of No-Tillage on Field Microclimate and Yield of Winter Wheat. *Agronomy* **2024**, *14*, 3075. https://doi.org/10.3390/agronomy14123075

Academic Editor: Tie Cai

Received: 12 November 2024
Revised: 19 December 2024
Accepted: 20 December 2024
Published: 23 December 2024

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1. Introduction

The NCP is one of the major grain producing areas in China, playing a crucial role in ensuring national food security. Double cropping of winter wheat and summer corn is the predominant grain planting method in this region [1]. During the planting of winter wheat in this area, there are issues, such as multiple agricultural machinery operations, low efficiency, and high production costs. Compared to traditional tillage, no-till has advantages, including reducing the number of agricultural machinery operations, improving production efficiency, protecting soil structure, increasing soil water retention capacity, and enhancing soil fertility. Additionally, no-till can prevent soil erosion, protect the agricultural ecological environment, and contribute to the sustainable development of agriculture [2–5].

In the Loess Plateau, no-till with mulch is considered one of the best tillage systems for increasing wheat water storage and yield, as well as improving water use efficiency and conserving energy [6]. However, compared to traditional tillage, no-till often faces controversy regarding its impact on crop yield and its adaptability in different agricultural environments [7–9], which limits its widespread application, especially in winter wheat production in the NCP [10].

Farmland microclimate refers to the climate within a small, localized area near the field surface, commonly represented by the values of agrometeorological elements, such as air temperature, air humidity, radiation, wind speed, and soil temperature and moisture in the near-surface layer of the farmland. The impact of soil tillage systems on the vertical distribution of the farmland microclimate has practical significance both theoretically and in practice, as it can alter the microclimate within the farmland ecosystem, thereby affecting soil moisture, nutrients, and crop yield [6]. The no-till sowing technology for wheat minimally disturbs the soil structure while retaining a large amount of above-ground crop residue, which has a certain impact on the farmland microclimate. Under no-till conditions, the undisturbed crop residue layer acts as a barrier to reduce soil evaporation and respiration. No-till improves water retention compared to conventional tillage, resulting in increased soil moisture storage [11]. Conservation tillage, which involves no or reduced soil disturbance (no-till or reduced tillage), is one of the effective ways to alleviate crop drought [12,13]. From the regreening stage to the maturity of winter wheat, the soil moisture content in each soil layer under no-till with straw mulch is higher than that under traditional tillage [14]. Most studies have shown that conservation tillage can improve crop water use efficiency [4–6,14–16].

No-till with straw mulch delays the growth process, prolongs the grain-filling duration, enhances the capacity for dry matter transport to grains, and increases the number of grains per spike and thousand-grain weight of winter wheat, compared to traditional tillage, thereby improving the grain yield of winter wheat [17]. Compared to traditional rotary tillage, no-till wheat has a slight increase in the number of ears, grains per ear, and thousand-grain weight, with a yield increase of 3.2% [18]. In the dryland areas of northern China, compared to conventional tillage, less tillage increases the yield of spring maize by 13–16% and winter wheat by 9–37%, while the yield under no-till is very close to that of conventional tillage [4]. Under ambient and warming conditions, conservation agriculture (permanent crop residue cover and no-till) maintains similar winter wheat yields to traditional agriculture (crop residue removal and annual tillage) [19]. Less tillage and no-till are effective measures to increase corn yields in dryland areas [20,21] and can also reduce the uncertainty of crop yields between years [22–24]. Guo et al. [25] demonstrated through a 12-year long-term conservation tillage experiment in Weibei Upland Plateau that in the winter wheat-fallow-spring maize rotation cycle, the average yield of crops under no-till was 1.6% higher than that under traditional tillage. In the NCP, long-term no-till for winter wheat can improve water use efficiency by reducing deep root distribution and water uptake, but continuous no-till can increase soil compaction, leading to a decrease in yield [26]. In southern China, a strategy based on no-till and rotary tillage (rotating one year of rotary tillage with three years of no-till) could reduce the negative impacts of continuous no-till and enhance profitability through increased yields, thereby maintaining the sustainability of rice production [27]. Pittelkow et al. [7] compared the yield differences between no-till and traditional tillage for 48 crops in 63 countries. Overall, no-till reduced crop yields; however, when combined with straw return and crop rotation, no-till could produce yields equivalent to or higher than traditional tillage. Of course, yield is only one component of the agricultural system, and there is an urgent need to optimize tillage methods based on environmental index [28].

Although numerous studies have been conducted on wheat yield and water use efficiency under no-till direct seeding by predecessors [4,6,17,18,26,27], there are fewer reports on the impact of tillage systems on the microclimate in wheat fields. Research on the effects of no-till practices on field microclimate and how the field microclimate

influences wheat yield has not been reported. This study conducted research on no-till direct seeding technology for winter wheat in the double-cropping area of winter wheat and summer maize in the NCP. The purpose is to compare the changes in microclimate under two tillage methods and the impact of microclimate on wheat grain yield.

2. Materials and Methods

2.1. Overview of the Experimental Site

The experiment was conducted from 2023 to 2024 at the National Precision Agriculture Demonstration and Research Base in Xiaotangshan, Changping, Beijing (40°21′ N, 116°34′ E, altitude 36 m). The annual average temperature in the experimental area is 10–13 °C, with an average daily sunlight duration of 6.5–8.5 h and an annual average precipitation of 602 mm, with 80% of the precipitation concentrated from June to August. The soil type is fluvo-aquic soil, and the main physical and chemical properties of the soil in the 0–20 cm layer are as follows: pH value of 7.62, organic matter content ranging from 5.8 to 20.0 g kg^{-1}, total nitrogen is 1.0–1.2 g kg^{-1}, nitrate nitrogen is 3.16–14.82 mg kg^{-1}, available phosphorus is 3.14–21.18 mg kg^{-1}, and available potassium is 86.83–120.62 mg kg^{-1}.

2.2. Experimental Materials

2.2.1. Equipment for No-Till and Conventional Wheat Sowing and Fertilization

A navigation-based Internet of Things (IoT) wheat sowing and fertilization machine is used for no-till direct seeding operations (NT). This machine, as shown in Figure 1, based on the 2BMQF-6/12 no-till seeder (Luoyang Xinle Machinery Equipment Co., Ltd., Luoyang, China), is equipped with a wheat sowing and fertilization IoT monitoring controller (NERCITA, Beijing, China) for monitoring and recording information on sowing rates, fertilization amounts, and operation trajectories. The navigation controller (Nongxin Technology Co., Ltd., Beijing, China) is used for tractor navigation and operational control, while the sowing and fertilization fault alarm controller (Changzhou Huaiyu Electronics Co., Ltd., Changzhou, China) monitors for any failures in seed and fertilizer distribution across the 12-row sowing and 6-row fertilization systems and then alerts the operator. The main components of the no-till seeder platform include a disc sawtooth furrow opener, a hard residue shoe-type opener, a dual-chamber dual-tube seed distribution system, and a roller for soil compaction. This machine is capable of simultaneously performing residue removal, furrowing, fertilization, seeding, and packing operations in a single pass. It employs a wide-narrow row planting system, with wide rows at 22 cm and narrow rows at 13 cm, while the fertilization position is 3–5 cm below the seed placement. In contrast, conventional tillage involves two passes of rotary tillage followed by seeding and fertilization with a 2BFX-24 seeder (Shijiazhuang Agricultural Machinery Co., Ltd., Shijiazhuang, China) at a uniform row spacing of 15 cm. The seeding speed during these operations ranges from 5 to 8 km h^{-1}.

2.2.2. Environmental Monitoring System

An environmental monitoring system was set up to monitor changes in air temperature and humidity in the wheat field, as well as soil temperature and humidity, see Figure 2. The air temperature and humidity sensor (model HSTL-BXYWS, Beijing Huakong Xingye Technology Development Co., Ltd., Beijing, China) has a measurement range of 0% RH to 100% RH for humidity, with an accuracy of ±4.5% RH, and a measurement range of −40 °C to 120 °C for temperature, with an accuracy of ±0.5 °C. The output signal is 4–20 mA. The soil temperature and humidity sensor (model HSTL-102STR, Beijing Huakong Xingye Technology Development Co., Ltd., Beijing, China) has a measurement range of 0 to 100% for soil relative humidity, with an accuracy of ±2%, and a measurement range of −40 °C to 80 °C for soil temperature, with an accuracy of ±0.2 °C. The output signal is 4–20 mA. The data acquisition module (model DAM0888, Beijing Juying Aoxiang Electronics Co., Ltd., Beijing, China) collects sensor data through its current analog input ports and transmits the data via the GSM network to a cloud platform for storage. The environmental

monitoring system is powered by a solar panel, enabling continuous data collection in the wheat field.

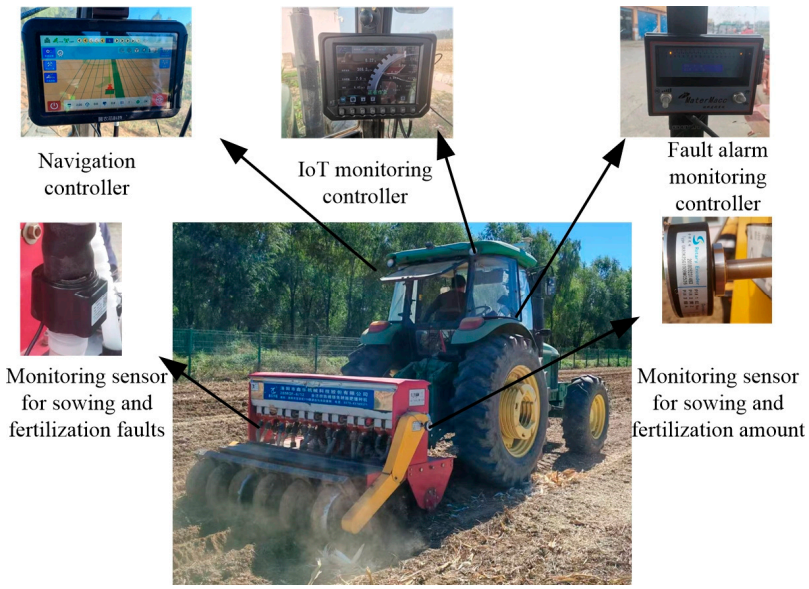


Figure 1. Navigation-based Internet of Things wheat seeding and fertilizer machine.

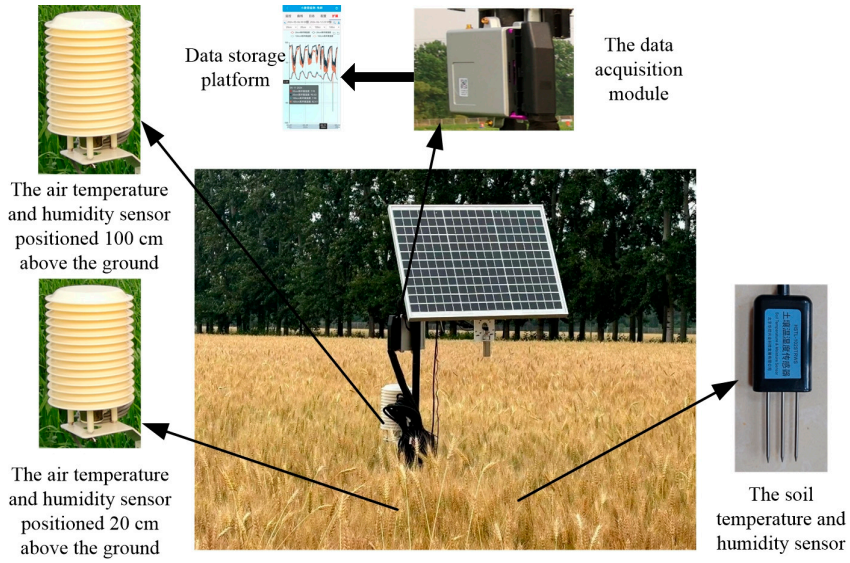


Figure 2. Environmental monitoring system.

2.3. Experimental Methods

2.3.1. Experimental Design

Treatment 1 was no-tillage sowing (NT), and treatment 2 was conventional tillage (CT). Sowing occurred on 6 October 2023, and harvesting took place on 12 June 2024. The preceding crop was silage summer maize. The plot size was 500 m^2 (50 m × 10 m), with three replicates in a randomized block design. The wheat variety tested was Jingdong 22 (Provided by the Wheat Research Institute of Beijing Academy of Agriculture and Forestry Sciences), with a base fertilizer of diammonium phosphate (N 15%, P_2O_5 42%) applied at a rate of 375 kg ha^{-1}. Urea (N 46%) was applied at a rate of 225 kg ha^{-1} during the wheat jointing stage. The seeding rate for both treatments was 270 kg ha^{-1}, and the irrigation method used was a movable spray irrigation system. The total irrigation amount during the wheat growth period was 180 mm, including 22.5 mm after sowing, 45 mm for the pre-wintering stage, 22.5 mm for the erecting stage, 45 mm for the jointing stage, 22.5 mm

for the anthesis stage, and 22.5 mm for the grain-filling stage. Other field management practices followed local production habits, and there were no severe pests or diseases during the wheat growth period.

2.3.2. Data Collection and Measurement Methods

Air temperature, humidity, and soil moisture content: An environmental monitoring system was utilized to measure air temperature and relative humidity at 20 cm and 100 cm above the wheat field surface, and soil moisture content at 20 cm below the ground. The data collection period for air temperature and relative humidity was from 6 May 2024, to 12 June 2024 (the wheat flowering time was on 5 May 2024), and for soil moisture content, it was from 6 May 2024, to 20 May 2024, with both data collection intervals set at 1 h. Plant moisture content and yield: Seven days before wheat harvest, approximately 20 representative single stems and 20 ears were collected from each plot. The samples underwent steam killing for 30 min at 105 °C, followed by drying at 75 °C until a constant weight was achieved. During harvest, three representative points with uniform growth were selected along the diagonal direction of each plot, and 3 m^2 of wheat was manually harvested at each sampling point.

2.4. Data Analysis

Data were organized using Microsoft Excel 2007, and statistical analysis was conducted using SPSS 25.0 software. The least significant difference (LSD) method was used to test for significant differences.

3. Results

3.1. Air Temperature at 20 cm and 100 cm Above the Ground During the Wheat Grain-Filling Stage (69–89)

As shown in Figure 3, the trends of the average air temperature at 20 cm above the ground during the wheat grain-filling stage were similar for both tillage methods: a gradual decline followed by a rapid increase, then a slower rise to a peak, after which the temperature gradually and rapidly decreased. The minimum values all occurred at 5:00 for both tillage methods, while the maximum values were observed at 14:00. During the wheat grain-filling stage, from 6:00 to 23:00, the average air temperature at 20 cm above the ground under no-till direct seeding was lower than that under conventional tillage, with reductions ranging from 0.4% to 10.4%. From 1:00 to 5:00, the average air temperature at 20 cm under no-till direct seeding was slightly higher than that under conventional tillage. The difference in the average air temperature at 20 cm between the two tillage methods was more significant from 8:00 to 18:00, with an average decrease of 8.1% under no-till direct seeding compared to conventional tillage.

The trend of the average air temperature changes at 100 cm above the ground (canopy) during the winter wheat grain-filling stage was basically the same as that at 20 cm for both no-till direct seeding and conventional tillage (Figure 4): a gradual and slow decrease from 0:00 to 5:00, with the lowest value at 5:00; a rapid increase from 6:00 to 10:00, a slow increase from 10:00 to 14:00, reaching the highest value at 14:00; and a slow decrease from 14:00 to 17:00, a rapid decrease from 17:00 to 20:00, and a slow decrease from 20:00 to 23:00. During the wheat grain-filling stage, the average canopy temperature under no-till direct seeding was lower than that under conventional tillage from 0:00 to 23:00, with a decrease of 0.5% to 8.1%. Notably, from 10:00 to 6:00, the canopy temperature under no-till direct seeding was significantly lower than that under conventional tillage.

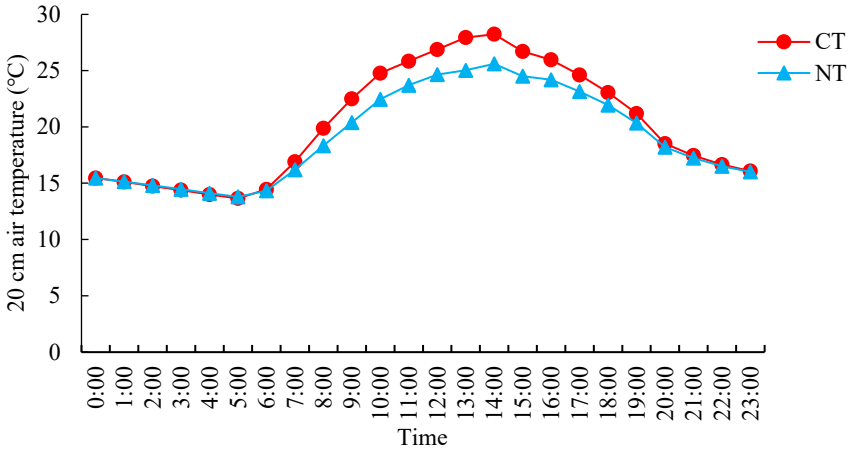


Figure 3. The average air temperature at 20 cm above the ground during the grain-filling stage (69–89) of winter wheat in the Beijing area.

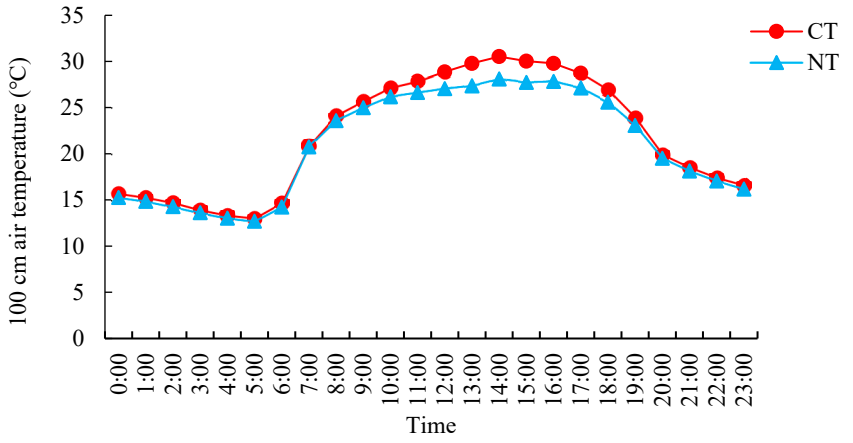


Figure 4. The average air temperature at 100 cm above the ground during the grain-filling stage (69–89) of winter wheat in the Beijing area.

3.2. Relative Humidity of the Air at 20 cm and 100 cm Above the Ground During the Wheat Grain-Filling Stage (69–89)

As shown in Figure 5, the trend of the average relative humidity of the air change at 20 cm above the ground during the grain-filling period of winter wheat under no-till direct seeding was basically the same as that under conventional tillage: it generally rises slowly from 0:00 to 7:00, with the maximum value occurring at 7:00. It drops rapidly from 7:00 to 12:00, and the rate of decline slows down after 12:00, with the minimum value appearing at 14:00, followed by a slow rise until 18:00, then it rises rapidly from 18:00 to 20:00, and afterwards, it continues to rise slowly. The overall trend of change in the average relative humidity of the air at 20 cm above the ground during the grain-filling period of wheat under both tillage methods was opposite to the trend of change in the average air temperature at 20 cm above the ground (Figure 3). The average relative humidity of the air at 20 cm above the ground during the grain-filling period of wheat under no-till direct seeding was greater than that under conventional tillage, especially from 8:00 to 19:00, when it was significantly higher than that of conventional tillage, increasing by 6.0% to 18.4%. During other time periods, the difference in the average relative humidity of the air at 20 cm above the ground between the two tillage methods was smaller.

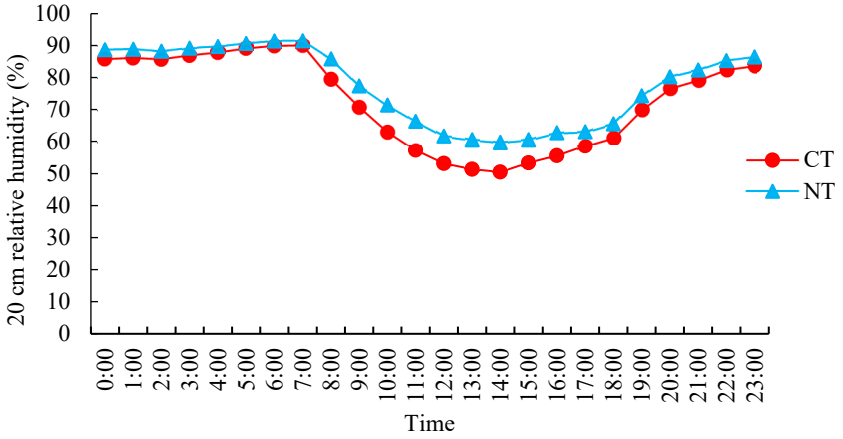


Figure 5. The average relative humidity of the air at 20 cm above the ground during the grain-filling stage (69–89) of winter wheat in the Beijing area.

The trend of the average air relative humidity of the air changes at 100 cm above the ground during the winter wheat grain-filling stage showed certain differences between no-till direct seeding and conventional tillage compared to the 20 cm level (Figure 6). Both tillage methods exhibited the following pattern: a gradual and slow increase from 0:00 to 6:00, followed by a slow decrease, with the maximum value occurring at 5:00, which was also the maximum value of the day; from 6:00 to 10:00, there was a rapid decrease, and then the rate of decrease gradually slowed down, reaching the minimum value at 14:00 or 15:00. After that, it slowly increased until 18:00, and then rapidly increased from 18:00 to 22:00. During the wheat grain-filling stage, the average relative humidity of the air at 100 cm above the ground under no-till direct seeding was higher than that under conventional tillage from 8:00 to 19:00, with an increase of 1.2% to 13.8%. Furthermore, from 10:00 to 18:00, the average relative humidity of the air under no-till direct seeding was significantly higher than under conventional tillage. From 0:00 to 8:00 and 19:00 to 23:00, the average relative humidity of the air at 100 cm above the ground under no-till direct seeding was slightly lower than that under conventional tillage.

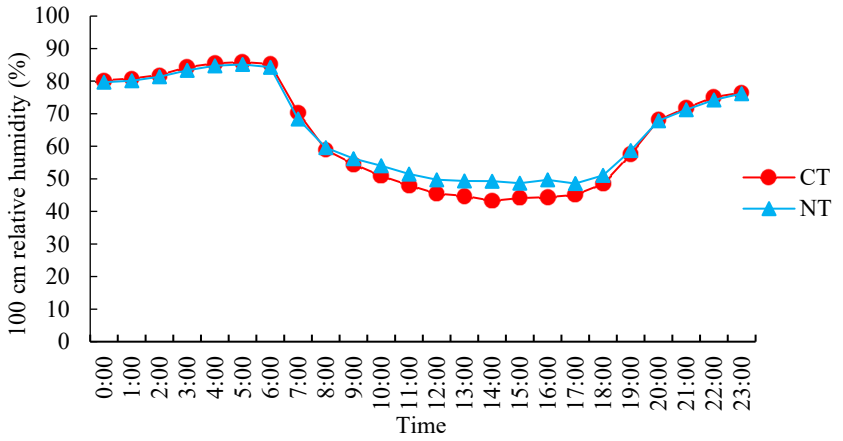


Figure 6. The average relative humidity of the air at 100 cm above the ground during the grain-filling stage (69–89) of winter wheat in the Beijing area.

3.3. Soil Moisture Content at 20 cm Below the Ground at the Early Stage of Wheat Grain-Filling (69–75)

During the early grain-filling period (15 days after flowering), in the absence of effective precipitation and artificial irrigation, the soil moisture content at 20 cm below the ground under both no-till direct seeding and conventional tillage methods showed a gradual decrease (Figure 7). On 14 May, the average soil moisture content at 20 cm below

the ground decreased by 10.6% and 15.9%, respectively, compared to 6 May. The average soil moisture content at 20 cm below the ground under no-till direct seeding was greater than that under conventional tillage, increasing by 3.1% to 11.2%. From 6 May to 14 May and from 17 May to 20 May, the difference in the average soil moisture content at 20 cm below the ground between the two tillage methods showed a gradual increase. Compared to conventional tillage, the average soil moisture content of no-till direct seeding increased by 4.7%, 11.2%, 3.1% and 4.9% on 6 May, 14 May, 17 May and 20 May, respectively. The above results indicated that under the same irrigation period and amount of irrigation, no-till direct seeding was more conducive to maintaining soil moisture content in the tillage layer of wheat fields and reducing water evaporation.

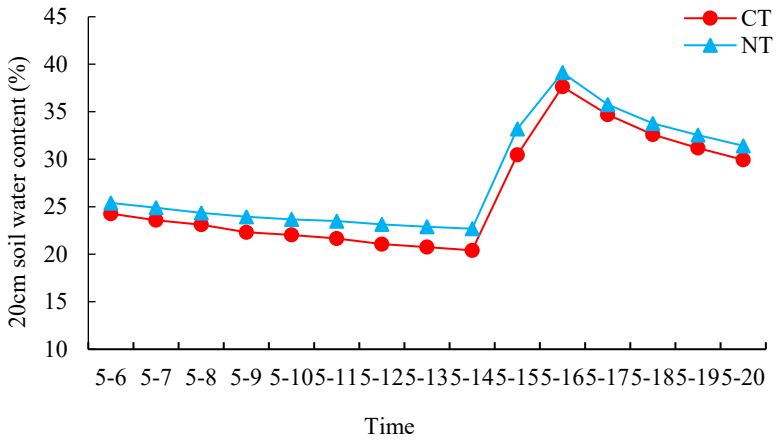


Figure 7. The average soil moisture content at 20 cm below the ground at the beginning of the grain-filling stage (69–75) of winter wheat in the Beijing area.

The watering began at 9:30 am on 15 May, and the irrigation amount was 30 mm.

3.4. Moisture Content of Wheat Plants and Spike Moisture Content Before Harvest (86)

The moisture content of wheat plants and spike moisture content were measured 7 days before harvest, and the results are shown in Table 1. The moisture content of wheat plants and spike moisture content under no-till direct seeding were significantly higher than those under conventional tillage. The dry weight of a single stem and single spike of wheat under no-till direct seeding were significantly greater than those under conventional tillage. In other words, at the end of the wheat grain-filling stage, the greenness retention and dry matter accumulation of wheat plants under no-till direct seeding were significantly better than those under conventional tillage, which is beneficial for grain-filling and, thus, increases grain weight.

Table 1. Moisture content of wheat plants and spike moisture content in the Beijing area.

Treatment	Plant Moisture Content (%)	Dry Weight per Stem (g)	Spike Moisture Content (%)	Dry Weight per Ear (g)
NT	49.35 ± 1.26 A	2.67 ± 0.04 a	42.02 ± 0.87 A	1.64 ± 0.04 a
CT	35.69 ± 0.85 B	2.49 ± 0.10 b	30.30 ± 1.03 B	1.55 ± 0.02 b

Different uppercase and lowercase letters in the same column indicate very significant ($p < 0.01$) and significant ($p < 0.05$) differences between treatments, respectively.

3.5. Wheat Yield and Yield Components

The grain yield of winter wheat under no-till direct seeding was higher than that under conventional tillage, although the difference was not significant (Table 2). The main reason that the wheat yield of the no-tillage direct seeding method was higher than that of conventional tillage was that the increase in thousand-grain weight and grain number

per spike compensated for the yield reduction caused by the decrease in the number of harvested spikes. Specifically, the number of harvested spikes using no-till direct seeding was significantly lower than that of conventional tillage. In contrast, the thousand-grain weight was significantly higher under no-till direct seeding than that under conventional tillage, reflecting an increase of 7.9%, while the grain number of spike was higher than that under conventional tillage. The difference in the number of spikelets between the two tillage methods was very small. However, the number of sterile spikelets under no-till direct seeding was significantly lower than that under conventional tillage, with a decrease of 8.6%. This might be one of the reasons why no-till direct seeding had a higher number of grains per spike compared to conventional tillage.

Table 2. Wheat yield and yield components in the Beijing area.

Treatment	Spikelet Numbers	Numbers of Sterile Spikelet	Spike Numbers (10^4 ha^{-1})	Grain Numbers per Spike	Thousand-Grain Weight (g)	Grain Yield (kg ha^{-1})
NT	16.33 ± 0.55 a	2.45 ± 0.10 b	605 ± 19 b	29.98 ± 0.60 a	45.24 ± 0.18 a	7413 ± 233 a
CT	16.23 ± 0.40 a	2.68 ± 0.18 a	678 ± 14 a	29.08 ± 0.33 a	41.93 ± 0.44 b	7218 ± 232 a

Different lowercase letters in the same column indicate significant difference ($p < 0.05$) between treatments.

This study was carried out at one location throughout the course of a winter wheat growing season. Given that field trials are greatly affected by environmental and climatic conditions, further experiments are required to derive more conclusive and representative conclusions on the impact of no-till direct seeding and conventional tillage on the microclimate in wheat fields, as well as the influence of these microclimates on yield.

4. Discussion

4.1. Effects of Different Tillage Methods on Microclimate in Wheat Fields

The growth, development, and yield formation of wheat plants are closely related to the microclimate in the fields, and different tillage methods have varying impacts on the microclimate. During the later stages of winter wheat growth, straw mulching improves the above-ground microclimate, which is beneficial for increasing yield and water use efficiency [29]. In the later stages of maize growth, the air temperature in no-till maize fields is lower than that in conventionally tilled fields [30]. This study indicated that during the grain-filling stage of winter wheat, the average air temperature at 20 cm above the ground under no-till direct seeding was slightly higher than that under conventional tillage during the period from 1:00 to 5:00. However, it was lower than that of conventional tillage from 6:00 to 23:00, and especially significantly lower during the period from 8:00 to 18:00, with an average reduction of 8.1%. The average air temperature at 100 cm above the ground (canopy level) under no-till direct seeding was lower than that under conventional tilling, especially during the period from 10:00 to 18:00, when it was significantly lower than conventional tillage, with an average reduction of 6.1%. This was consistent with the findings of Irmak et al. [30], but contrary to the conclusion that no-till increases the air temperature above the canopy during the grain-filling stage of winter wheat compared to conventional tillage [31], which might be caused by differences in growth environments or climatic factors, especially differences in precipitation during the growth period of winter wheat. According to the research findings of Han et al. [31], the advantage of the no-till system is its ability to improve the vertical distribution of the population microclimate. Compared to conventional tillage, no-till practices enhance the relative humidity of the air in the upper, middle, and lower parts of the winter wheat canopy during the grain-filling period. In this study, the average relative humidity of the air at 20 cm above the ground under no-till direct seeding was higher than that under conventional tillage, especially during the period from 8:00 to 19:00, when it was significantly higher than conventional tillage, with an increase of 6.0% to 18.4%. The average relative humidity of the air at 100 cm above the ground under no-till direct seeding was slightly lower than that under

conventional tillage during the period from 0:00 to 7:00 and from 20:00 to 23:00, while it was higher than conventional tillage from 8:00 to 19:00, with a significant increase from 10:00 to 18:00, with an average increase of 9.2%. This was consistent with the above research conclusions. This study also found that during the grain-filling stage of winter wheat, the variation range of the average air temperature and humidity at 20 cm and 100 cm above the ground under no-till direct seeding was smaller than that under conventional tillage (Figures 3–6). The variation trends of the average air temperature and humidity at 20 cm and 100 cm above the ground under the two tillage methods were basically the same, and the variation trends of the air temperature and relative humidity of the air were opposite, meaning that when the air temperature was high, the relative humidity of the air was low.

Straw mulching reduces the evapotranspiration of winter wheat from the seedling stage to the maturity stage, with the mulched treatment showing a reduction of 47.4 mm in evapotranspiration compared to the non-mulched treatment [29]. Compared to traditional tillage, no-till on the Loess Plateau drylands improves the efficiency of precipitation storage during the fallow period, and the soil available water during the wheat planting period is significantly higher under no-till direct seeding than under the traditional methods [6]. The soil moisture content in the tillage layer during the regreening stage, grain-filling stage, and harvest stage of winter wheat under less tillage and no-till increase by 4.49%, 6.86%, and 7.88%, respectively, compared to traditional tillage methods [32]. The results of this study indicated that under the same irrigation period and amount of irrigation, during the early grain-filling stages of winter wheat, the average soil moisture content at 20 cm below the ground under no-till direct seeding was higher than that under conventional tillage, with an increase of 3.1% to 11.2%. This was basically consistent with the above research conclusions and the findings of Feng et al. [14]. The average soil moisture content at 20 cm below the ground under both no-till direct seeding and conventional tillage methods showed a trend of gradual decrease, and the difference between the two methods showed a trend of gradual increase with the delay of the growth period, which was also confirmed by the research results of Du et al. [32]. The period from 10:00 to 18:00 is a critical time for the growth and development of wheat plants in a day. In this study, during the grain-filling stage, the average air temperature at 20 cm and 100 cm above the ground under no-till direct seeding was significantly lower than that under conventional tillage, while the average relative humidity of the air was significantly higher than that under conventional tillage. In addition, the soil moisture content at 20 cm below the ground under no-till direct seeding was higher than that under conventional tillage. In conclusion, the vertical microclimate in the field during the grain-filling stage under no-till direct seeding was more suitable for the growth and development of wheat plants than conventional tillage, and was conducive to maintaining the greenness of wheat plants in the later growth phase and grain-filling, increasing grain weight and, thus, increasing yield.

4.2. Effects of Different Tillage Methods on Wheat Yield

The grain yield of wheat is determined by the product of the number of harvested spikes, the number of grains per spike, and the thousand-grain weight. Compared with conventional tillage, when the water supply during the growing season of winter wheat is less than or equal to 650 mm, no-till combined with straw mulching increases wheat yield by 36.56% under dryland agricultural conditions [33]. The yield of wheat with less tillage or no-till increases by 10.3% compared to conventional tillage, among which the increase of grain number per spike and 1000-grain weight are the main factors contributing to the increased production of wheat [32]. The three-year experimental results of Yang et al. [34] indicate that the average yield of no-till wheat is 5.7% higher than that of conventional tillage, with statistical significance in two of the three years. This is due to the significantly higher thousand-grain weight of no-till wheat over the three years and the significantly higher number of grains per spike in two of the three years compared to conventional tillage. The number of spikes harvested under conventional tillage is significantly higher than that of no-till, while there are no significant differences in grains per spike and thousand-

grain weight between the two tillage methods, and the yield of conventional tillage is significantly higher than that of no-till [31]. The results of this study demonstrated that the number of spikes harvested under no-till direct seeding was significantly lower than that under conventional tillage, with a decrease of 10.8%. This was consistent with the conclusions of Han et al. [31]. However, the thousand-grain weight under no-till direct seeding was significantly higher than that under conventional tillage, increasing by 7.9%, and the number of grains per spike was also higher, with an increase of 3.1%. The grain yield of wheat under no-till direct seeding was higher than that under conventional tillage, increasing by 2.7%, which was consistent with the research conclusions of Li et al. [17], Zhang et al. [18], Du et al. [32], Wu et al. [33], and Yang et al. [34], but opposite to the research conclusions of Li et al. [29] and Han et al. [31]. The reasons for this might include significant differences in soil fertility conditions among the experimental plots, substantial variations between different wheat varieties, or considerable discrepancies in the experimental design. In this study, the main reason why the yield of no-till direct seeding is higher than that of conventional tillage was that the combined increase in both grain number per spike and the thousand-grain weight (especially the thousand-grain weight) compensates for the reduction in yield caused by the decrease in the number of harvested spikes. This was basically consistent with the research conclusions of Li et al. [17], Du et al. [32], and Yang et al. [34]. Additionally, this study found that the number of sterile spikelets under no-till direct seeding was significantly lower than that under conventional tillage, with a decrease of 8.6%, which might be one of the main reasons why no-till direct seeding has a higher number of grains per spike compared to conventional tillage.

During the later growth stage of wheat, the dry matter accumulation of vegetative organs, such as stems and leaves, under the straw mulching treatment is significantly higher than that without mulching. The excessive growth of vegetative organs consumes a large amount of nutrients, resulting in a reduced allocation of photosynthetic products to grains [35]. During the harvest period, the dry weight per wheat plant under less tillage and no-till treatments increased by 0.35 g, and the dry weights of spikes, leaves, and stems increased by 13.3%, 10.5%, and 37.0%, respectively, compared to conventional tillage [32]. The results of this study indicated that seven days before the harvest of winter wheat, the dry weight per stem and the dry weight per spike under no-till direct seeding were significantly greater than those under conventional tillage, increasing by 6.1% and 6.4%, respectively. This was basically consistent with the research conclusion of Du et al. [32]. In the late grain-filling stage of winter wheat, no-till direct seeding not only increased the dry matter accumulation in vegetative organs, such as stems and leaves, but also enhanced the dry matter accumulation in the reproductive organ spikes, which was somewhat different from the conclusions of Li et al. [35]. In this study, seven days before the harvest of winter wheat, both the plant moisture content and the spike moisture content under no-till direct seeding were extremely significantly higher than those under conventional tillage, increasing by 38.3% and 38.7%, respectively. In other words, the greenness retention of plants under no-till direct seeding during the late grain-filling stage of winter wheat was significantly better than that of conventional tillage, effectively preventing the early senescence of wheat plants caused by meteorological factors, such as dry hot wind, drought, and high temperatures, which was beneficial for grain-filling and ultimately increased grain weight. This was consistent with the conclusion that soil moisture storage under conventional tillage is lower than that under no-till, leading to earlier senescence of corn plants in the later stages of growth [30]. No-till direct seeding can provide a suitable microclimate for wheat growth compared to conventional tillage. It not only maintains the yield of winter wheat but also reduces the costs associated with the sowing process, improves operational efficiency, and increases soil moisture content. This study provides valuable guidance for the implementation of conservation tillage practices in the NCP, where groundwater overextraction is a severe issue. It can effectively promote the development of sustainable agriculture in this region and beyond.

5. Conclusions

During the wheat grain-filling period, from 10:00 to 18:00, the average air temperature at 20 cm and 100 cm above the ground under no-till direct seeding was significantly lower than that of conventional tillage, while the average relative humidity of the air was significantly higher. At the beginning of grain-filling, the average soil moisture content at 20 cm below the ground under no-till direct seeding was higher than that of conventional tillage. Seven days before the wheat harvest, the moisture content of plants and spike under no-till direct seeding were both extremely significantly greater than those of conventional tillage, and the dry weight per plant and the dry weight per spike were significantly greater than those of conventional tillage. Consequently, the thousand-grain weight of wheat under no-till direct seeding was significantly higher than that of conventional tillage, increasing by 7.9%. The number of wheat sterile spikelets under no-till direct seeding was significantly lower than that under conventional tillage, with a decrease of 8.6%, and the number of grains per spike was higher than that of conventional tillage, with an increase of 3.1%. The yield of no-till direct seeding was 2.7% higher than that of conventional tillage.

Author Contributions: Conceptualization, C.Z. and Z.D.; methodology, Z.D., J.Z., S.Y. and C.Z.; validation, C.Z.; formal analyses, J.Z., Z.D., S.L. and S.Y.; investigation, Z.D., S.Y., S.L., P.F., J.W. and Y.L.; resources, C.Z. and X.W.; software, P.F.; data curation, Z.D., S.L., P.F., Y.L. and X.W.; writing—original draft, Z.D.; writing—review and editing, J.W., C.Z., J.Z. and S.Y.; funding acquisition, C.Z. and X.W.; supervision, C.Z., J.Z. and S.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Major Project of Yunan Science and Technology (202302AE09002002), the Science and Technology Project of Wuhu City (20231y05), and the Hebei Academy of Agriculture and Forestry Sciences Youth Science and Technology Talent Domestic Training Project (C24R0307).

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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