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Impact of Subsoiling on Cultivated Horizon Construction and Grain Yield of Winter Wheat in the North China Plain

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Abstract: In order to explore the effects of subsoiling tillage measures on the construction of soil cultivated horizon and the yield and water use efficiency of winter wheat in the North China Plain, three tillage methods, including no tillage (PZ), rotary tillage (PR), and subsoiling (PS), combined with straw returning measures were implemented in the winter wheat season in Xinxiang, Henan Province from 2016 to 2018. The effects of tillage measures on the improvement of cultivated land quality and the water saving and yield increase of winter wheat were investigated. The results showed that compared with no-tillage treatment, subsoiling significantly reduced soil bulk density by 8.88% and increased soil porosity by 13.04% in 20–40 cm soil layer; significantly reduced soil compaction by 56.96% in 0–40 cm soil layer; subsoiling combined with straw returning significantly increased soil organic carbon content in plough layer of winter wheat, whereas rotary tillage decreased soil organic carbon content. Subsoiling is more conducive to soil moisture movement to the deep layer after irrigation or rainfall, and the water consumption of subsoiling is the largest in the whole growth period of winter wheat. Subsoiling could better coordinate the relationship between water consumption and yield, which increased yield by 34.48–38.10% and water use efficiency by 19.57–21.96% compared with no-tillage treatment, respectively. Therefore, subsoiling before sowing combined with straw returning was beneficial to the reasonable construction of soil cultivated horizon, and significantly improved the yield and water use efficiency of winter wheat under the climatic conditions in the North China Plain.

Keywords: subsoiling; cultivated horizon construction; winter wheat; yield; water use efficiency; North China Plain

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1. Introduction

The North China Plain (NCP) is an important grain production base in China which is very important to ensure national food security. This region accounts for 18% of the national cultivated land but produces 23% of the grains with only 6% of water resources [1]. However, the decreasing water resources, gradual degradation of cultivated land quality, and the overdraft of soil fertility have threatened the sustainable development of local agriculture. Suitable tillage methods combined with scientific irrigation are adopted to construct a reasonable cultivated horizon structure to improve the quality of cultivated land and water use efficiency as well as alleviate scarcity of water and cultivate land resources [2].

Rotary tillage before sowing of winter wheat, no-tillage sowing of summer maize, and flooding irrigation have been applied for a long time in the North China Plain, resulting in shallow soil tillage layer, compact soil structure, thick and hard plow pan, and poor soil quality [3]. Soil moisture and nutrients are mainly concentrated in the surface layer after rainfall, irrigation, and fertilization, so it cannot be effectively supplemented to the deep soil due to compact plow pan, which is averse to the construction of the optimal root structure of winter wheat, and furthermore caused lodging and decrease of crop stress resistance [4,5]. Studies have shown that subsoiling tillage can optimize the structure and improve the quality of soil arable layer as well as crop water and nutrient use efficiency [6,7]. Subsoiling provides an appropriate growth environment for crops by destroying the plow pan, reducing soil compactness, and promoting soil aeration and water storage capacity [8–10].

In recent years, the strategy of "Storing Grain in Land and Technology" was implemented by the China Agriculture and Rural Affairs Ministry, aiming at improving the comprehensive agriculture production capacity and ensuring grain security [11–13]. In the past decade, the increase in grain output in China comes from the increase in yield per unit and cultivation area. The increase in yield per unit is mainly due to the improvement of varieties, the optimization of farmland infrastructure, and the progress of farming technology (especially the contribution of technology); the increase in cultivation area is mainly related to the policy factors of the state to encourage grain production. Based on the limitation of cultivated land area and continuous population growth, improvement of the cultivated quality becomes one of the key factors for "Storing Grain in Land and Technology". Consequently, mechanical subsoiling is extensively popularized all over the nation as an important agronomic measure to promote cultivated land quality. However, most of the existing studies focus on the single effect of subsoiling on soil moisture and/or temperature properties, crop growth, etc. [2,14–17], and there is a lack of systematic research on the mechanism of the contribution of subsoiling tillage to soil cultivated horizon construction and wheat yield variation in the North China Plain. Accordingly, regarding the regional importance and the decline in the quality of cultivated land caused by the long-term use of traditional simplified planting mode in the region, the specific objectives of this study were (1) to clarify the influence mechanism on cultivated land quality improvement and grain production promotion by subsoiling, (2) to provide technical support for optimizing the structure of soil cultivated horizon in the North China Plain, and (3) to popularize subsoiling technology, and realize water-saving and yield-increasing of winter wheat in the region.

2. Materials and Methods

2.1. Details of Experimental Location

The field experiments were conducted at the comprehensive test site of the Farmland Irrigation Research Institute (Chinese Academy of Agricultural Science, CAAS) in Xinxiang (35°18′ N and 113°54′ E) from October 2016 to June 2018 wheat-growing seasons. The meteorological data were obtained based on a 60-year average from Xin Xiang Weather Station that is located 50 m from the experimental field. The average annual temperature was 14.1 °C, frost-free period was 210 d, sunshine duration was 2398.8 h, annual average evaporation was 2000 mm, and annual average rainfall was 588.8 mm. The rainfall was 468.4 mm and 573.7 mm from October 2016 to September 2017 and October 2017 to September 2018 in winter wheat–summer maize growth season, respectively, and 18.4% and 0.14% lower than that average rainfall 574.5 mm of a long term from 1951 to 2015. The rainfall of winter wheat growth seasons was 201.4 mm in 2017 and 218.6 mm in 2018, respectively. The distribution of precipitation and temperature during winter wheat growth period in 2016–2018 are shown in Figure 1.

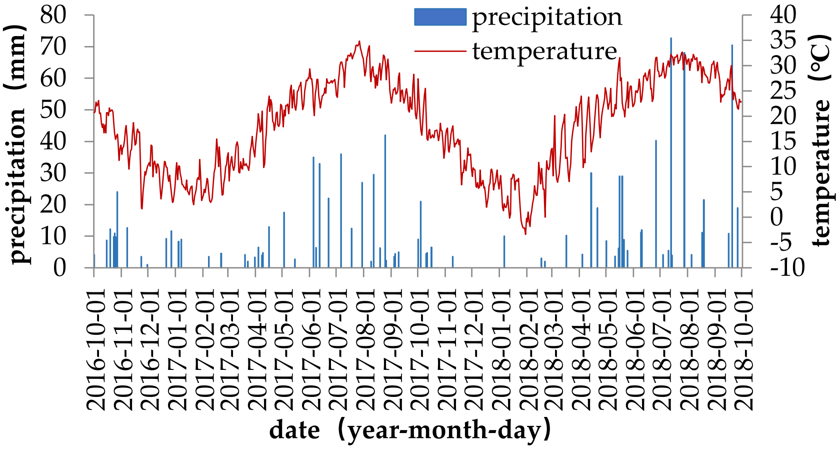

Figure 1. Distribution of precipitation and temperature during winter wheat growth period in 2016–2018.

The test soil was sandy loam, and its physical and chemical properties are shown in Table 1. The groundwater depth was greater than 5 m in the experimental site.

Table 1. Soil physical and chemical properties.

Soil Layers	Clay (<0.002 mm)	Silt (0.02~0.002 mm)	Sand (2~0.02 mm)	Soil Bulk Density	Field Capacity	pH	Ec	Alkaline Hydrolysis N	Available P	Exchangeable K	SOC
cm	%	%	%	$g \cdot cm^{-3}$	%		$\mu s \cdot cm^{-1}$	$mg \cdot kg^{-1}$	$mg \cdot kg^{-1}$	$mg \cdot kg^{-1}$	$g \cdot kg^{-1}$
0–20	4	55	41	1.57	21.79	8.82	201.15	58.08	22.56	120.22	12.36
20–40	3	57	40	1.59	19.62	8.95	170.59	33.29	14.79	70.21	6.59
40–60	9	45	46	1.54	21.43	8.67	165.96	19.61	4.36	69.68	5.26
60–80	10	48	42	1.45	19.72	8.89	210.02	15.26	3.25	65.36	4.36
80–100	7	21	72	1.48	20.00	9.21	203.60	9.01	2.69	32.56	3.09
Mean	7	45	48	1.53	20.51	8.91	190.26	27.05	9.53	71.61	6.33

Ec, electrical conductivity; SOC, soil organic carbon; filed capacity was gravimetric water content under −33 kPa pressure.

2.2. Experimental Design

Winter wheat variety "Bainong 207" (*Triticum aestivum* L.) was sown with seeding rate of 225 $kg \cdot ha^{-1}$ on 20 October in 2016 and 22 October in 2017 and harvested on 3 June in 2017 and 5 June in 2018, respectively. Compound fertilizer of 750 $kg \cdot ha^{-1}$ ($N–P_2O_5–K_2O$:15–15–15, total nutrient ≥45%) was applied as basal and 375 $kg \cdot ha^{-1}$ urea (total nitrogen ≥46.4%) was applied as topdressing at jointing stage.

The experiment was randomized block designed and three treatments were set as (1) no-tillage (PZ), wheat sowing directly without any soil tillage after harvest of previous crop, (2) rotary tillage (PR), rotary tillage at depth of 10–15 cm before wheat sowing by using a medium–high box rotary tillage machine (1GKN-220A1, Shuangtian Machinery Manufacturing Co., Ltd., Hebei, China), and (3) subsoiling (PS), soil deep loosening at depth of 35–40 cm before wheat sowing by using a omnidirectional deep loosening machine (1S-250, Dahua Machinery Co., Ltd., Shandong, China) with four arc inverted ladder shovels (Figure 2). The shovel spacing was 62 cm, and the working width was 250 cm. Each treatment had three replicates (total of nine plots) and the plot area was 25 m length × 8 m width. All the previous maize straws were crushed and returned to the field. Irrigation of each treatment was carried out consistently according to the seasonal rainfall. Border irrigation was applied twice with the amount of 750 $m^3 \cdot ha^{-1}$ at the jointing stage and heading stage of winter wheat in 2017 and 2018, respectively. Each adjacent plot was 50 cm separated and irrigated singly via a polyvinyl chloride pipe fitted with a high-precision water meter. Pests and weeds control were executed in accordance with farmer practices in the experimental region. The types of pesticides were moderate, and doses of herbicides (10% wettable powder of benzene sulfonic lung, spray), insecticides (10% wettable powder of pyrimethanil, seed dressing combined spray), and fungicides (5% emulsion of abamectin, seed dressing) were used according to the pesticide instructions and pests and diseases of winter wheat.

Figure 2. Different tillage treatments before winter wheat sowing.

2.3. Sampling and Measurements

2.3.1. Soil Bulk Density and Porosity

At the mature stage of winter wheat (22 May 2017 and 28 May 2018 before harvest, respectively), soil profile depth of 0–40 cm was excavated in each treatment, and the soil bulk density of every 10 cm of soil layers was measured by cutting ring method (100 cm^3 in volume), and the soil porosity was calculated. Each treatment was repeated three times. The constant of soil specific gravity is 2.65 $g \cdot cm^{-3}$. Soil porosity was calculated by the following formula [18]:

$$Soil\ porosity\ (\%) = (1 - r/2.65) \times 100\% \quad (1)$$

r, soil bulk density ($g \cdot cm^{-3}$).

2.3.2. Soil Compaction

Soil compaction of 0–40 cm soil layer was measured by a soil penetrometer (SC-900, Spectrum Technologies, Inc., USA) in triplicate at the head (1/5 ridge length), middle (1/2 ridge length), and tail (4/5 ridge length) of each treatment at the maturity stage of winter wheat (22 May 2017 and 28 May 2018 before harvest, respectively).

2.3.3. Soil Water Content

The soil moisture content of vertical direction 0–100 cm was measured with intervals of every 20 cm by oven-dried method at each growth period of winter wheat. The wet and oven-dried soil was weighed by an electronic balance (AR4202CN, Ohaus, Inc., USA) with a precision of 0.01 g. The measurement was added once before and after irrigation and/or rainfall. Soil water content was calculated by the following formula [18]:

$$w = (M_1 - M_2)/M_2 \times 100 \quad (2)$$

w, soil water content (gravimetric, %); M_1, wet soil weight (g); M_2, dry soil weight (g).

2.3.4. Soil Water Storage

Soil water storage was calculated by the following formula [19]:

$$W = r \times h \times w \times 10 \quad (3)$$

W, soil water storage (mm); *h*, soil layer depth (cm), depth of 100 cm soil layer with an interval of 20 cm; *r*, soil bulk density (g·cm^{-3}); *w*, soil moisture content (gravimetric, %).

2.3.5. Soil Organic Carbon

Before winter wheat harvest, soil mixed samples were collected at two layers of 0–20 cm and 20–40 cm from each plot on May 23, 2017, and May 29, 2018, respectively, and each treatment was repeated three times. The samples were dried naturally, and debris such as gravel and plant residues were removed. The samples were ground and sieved by 0.25 mm sieve. The organic carbon content was determined by the potassium dichromate oxidation method [20].

2.3.6. Crop Water Consumption

Field water consumption was calculated by water balance function [21]:

$$ET = I + P + U - R_f - D + (W_0 - W_t) \quad (4)$$

$$ET = I + P - D + (W_0 - W_t) \quad (5)$$

ET, water consumption (mm); *I*, irrigation amount (mm); *P*, precipitation (mm); *U*, groundwater recharge (mm), the groundwater level of experimental site was below 5 m and so it cannot be absorbed by crop, $U \approx 0$; R_f, surface runoff (mm) can be ignored due to flat terrain in the testing area; *D*, deep percolation within root zone (mm) can be calculated as sum of soil water storage (before irrigation) within 0~100 cm and irrigation amount (and/or rainfall), minus field capacity; W_0 and W_t (mm), soil water storage of time period initial and end, respectively.

2.3.7. Grain Yield

The grain yield was measured in three quadrats, each with an area of 4 m^2 from each plot under 13% moisture content at maturity of winter wheat.

2.3.8. Water Use Efficiency (WUE)

Water use efficiency was calculated by the following formula [22]:

$$WUE = Y/ET \quad (6)$$

WUE, water use efficiency (kg·ha^{-1}·mm^{-1}); *Y*, grain yield (kg·ha^{-1}); *ET*, water consumption (mm).

2.4. Data Analysis

Statistical analyses were conducted via one-way analysis of variance (ANOVA) and least significant difference (LSD) test for significance at $p < 0.05$ using Data Processing System software (DPS; Institution of Agricultural Entomology, Zhejiang University, China). Standard deviation (SD) was calculated by Microsoft Excel 2010. The change trend of each treatment in two years were basically consistent according to the data results, so the differences between years were not considered and the statistical analyses were conducted for the data of 2017 and 2018, respectively.

3. Results

3.1. Effect of Tillage Methods on Soil Structure of Winter Wheat Farmland

3.1.1. Effect of Tillage Methods on Soil Bulk Density

Soil bulk density at 0–40 cm layer decreased significantly ($p < 0.05$) under PR and PS treatments (Table 2). Within 0–20 cm soil layer, soil bulk density decreased by 5.16% (PR, percent are differences between two values transferred into percent and that such a method is used for analyzing all measured parameters) and 7.74% (PS) in 2017, 5.33% (PR), and 6.67% (PS) in 2018 compared with PZ, respectively. The aforesaid corresponding declined proportions of soil bulk density were 8.81% (PR), 9.43% (PS), 5.77% (PR), and 8.33% (PS) at 20–40 cm soil layer compared with PZ. PR and PS treatments alleviated soil compactness caused by machinery working during sowing and harvesting periods. Furthermore, PS treatment reduces soil bulk density at 20–40 cm more obviously than 0–20 cm compared to PR treatment. Subsoiling can break the plow pan effectively and decrease the soil bulk density.

Table 2. Soil bulk density of plough layer under different tillage methods ($g \cdot cm^{-3}$).

Year	Treatments	0–20 cm	20–40 cm
2017	PZ	1.55 ± 0.02 [a]	1.59 ± 0.07 [a]
	PR	1.47 ± 0.02 [b]	1.45 ± 0.05 [b]
	PS	1.43 ± 0.03 [b]	1.44 ± 0.02 [b]
2018	PZ	1.50 ± 0.03 [a]	1.56 ± 0.05 [a]
	PR	1.42 ± 0.04 [b]	1.47 ± 0.08 [b]
	PS	1.40 ± 0.01 [b]	1.43 ± 0.03 [b]

PZ, no tillage; PR, rotary tillage; PS, subsoiling. Values in the same column with different letters differ significantly ($p < 0.05$). Mean value ± SD.

3.1.2. Effect of Tillage Methods on Soil Porosity

PR and PS treatments remarkably improved ($p < 0.05$) the soil porosity at 0–40 cm (Table 3). Within 0–20 cm soil layer, soil porosity increased by 7.27% (PR) and 10.91% (PS) in 2017, and 6.96% (PR) and 8.70% (PS) in 2018 compared with PZ, respectively. The corresponding increased proportions at 20–40 cm soil layer were 13.21% (PR), 14.15% (PS), 8.26% (PR), and 11.92% (PS), respectively. Amplification of PS treatment at 20–40 cm was higher than 0–20 cm compared to PR treatment. PS treatment enhanced the soil aeration as well as soil porosity due to destroyed plow pan.

Table 3. Soil porosity of plough layer under different tillage methods (%).

Year	Treatments	0–20 cm	20–40 cm
2017	PZ	41.51 ± 0.94 [b]	40.00 ± 1.53 [b]
	PR	44.53 ± 0.90 [a]	45.28 ± 1.08 [a]
	PS	46.04 ± 1.04 [a]	45.66 ± 0.47 [a]
2018	PZ	43.40 ± 0.99 [b]	41.13 ± 1.16 [b]
	PR	46.42 ± 1.38 [a]	44.53 ± 1.79 [a]
	PS	47.17 ± 0.36 [a]	46.04 ± 0.72 [a]

PZ, no tillage; PR, rotary tillage; PS, subsoiling. Values in the same column with different letters differ significantly ($p < 0.05$). Mean value ± SD.

3.1.3. Effect of Tillage Methods on Soil Compaction

Different degrees of plow pan were formed due to long-term mechanical roller compaction by small agricultural machinery under no-tillage and rotary tillage measures. A too-thick plow pan will increase the soil compactness and then prevent water infiltration and root growth, finally causing low fertilizer use efficiency and yield reduction. Through experimental observation, the depth of plow pan in the NCP region is about 15–30 cm from the surface soil, and the thickness is about 10–16 cm (Figure 3). PS treatment significantly decreased ($p < 0.05$) the soil compaction at 0–40 cm (Table 4) because of the destruction of plow pan. Compared to PR and PZ treatment, the decreasing ranges (average of 0–20 cm and 20–40 cm) of PS were 47.58% and 57.99% in 2017, and 31.77% and 54.36% in 2018, respectively. The PS treatment reduced soil compaction of cultivated horizon to varying degrees, which provided a suitable soil environment for the growth and development of winter wheat roots.

Figure 3. Position of cultivated horizon and plow pan in soil profile under rotary tillage and subsoiling.

Table 4. Soil compaction of plough layer under different tillage methods (MPa).

Year	Treatments	0–20 cm	20–40 cm
2017	PZ	2.30 ± 0.25 [a]	2.08 ± 0.55 [a]
	PR	1.85 ± 0.11 [a]	1.66 ± 0.38 [a]
	PS	0.89 ± 0.30 [b]	0.95 ± 0.18 [b]
2018	PZ	2.28 ± 0.44 [a]	2.19 ± 0.35 [a]
	PR	1.55 ± 0.34 [ab]	1.44 ± 0.20 [a]
	PS	1.05 ± 0.22 [b]	0.92 ± 0.10 [b]

PZ, no tillage; PR, rotary tillage; PS, subsoiling. Values in the same column with different letters differ significantly ($p < 0.05$). Mean value ± SD.

3.1.4. Effect of Tillage Methods on Soil Organic Carbon Content

Soil organic carbon (SOC) plays an important role in soil fertility and cultivated land quality improvement and affects crop yield. Changes in soil aeration and microenvironment by tillage methods lead to different degrees of decomposition of soil organic carbon. PS treatment significantly increased ($p < 0.05$) the SOC content at 0–40 cm compared with PZ in both years, whereas PR treatment was the opposite, especially at 0–10 cm (Table 5). The increasing range (average of 0–40 cm) of PS treatment was 14.06% in 2017 and 11.38% in 2018 compared with PZ treatment, respectively. The decreasing range (0–10 cm) of PR was 18.46% in 2017 and 11.10% in 2018 compared with PZ treatment, respectively.

Compared to no tillage, the depth of subsoiling was 35 cm, which reduced the chance of deep soil contacting air. The change of soil microenvironment after subsoiling may inhibit the decomposition of soil organic carbon by soil microorganisms, which is beneficial to the stability of soil organic carbon. At the same time, subsoiling causes less disturbance to the surface soil, which is more conducive to the structural stability of soil aggregates, thereby improving the fixation of soil organic carbon. However, the strong disturbance of rotary tillage on soil surface destroyed the soil aggregate structure. The loose soil environment was more useful for soil microbial activity, accelerated the mineralization and decomposition of soil organic carbon, and promoted the release of active components of soil organic carbon.

Table 5. Soil organic carbon content of plough layer under different tillage methods (g·kg^{-1}).

Year	Treatments	0–10 cm	10–20 cm	20–30 cm	30–40 cm
2017	PZ	11.05 ± 1.27 [b]	8.25 ± 0.78 [ab]	6.68 ± 0.84 [b]	5.46 ± 1.27 [b]
	PR	9.01 ± 0.53 [c]	7.59 ± 1.09 [b]	6.49 ± 1.10 [b]	5.38 ± 0.69 [b]
	PS	12.35 ± 0.46 [a]	8.99 ± 0.85 [a]	7.71 ± 1.27 [a]	6.81 ± 1.20 [a]
2018	PZ	11.08 ± 0.94 [a]	7.78 ± 0.77 [ab]	6.94 ± 1.09 [b]	6.11 ± 0.86 [b]
	PR	9.85 ± 0.51 [b]	7.19 ± 0.95 [b]	6.25 ± 0.73 [b]	6.02 ± 0.98 [b]
	PS	11.98 ± 0.70 [a]	8.25 ± 0.92 [a]	7.96 ± 1.22 [a]	7.35 ± 1.03 [a]

PZ, no tillage; PR, rotary tillage; PS, subsoiling. Values in the same column with different letters differ significantly ($p < 0.05$). Mean value ± SD.

3.2. Effect of Tillage Methods on Water Consumption Characteristics of Winter Wheat

3.2.1. Effect of Tillage Methods on Soil Water Storage

Different tillage measures have changed the structure of soil cultivated horizon, thereby affecting the distribution of soil water storage. Dynamic change trend of soil water was approximately consistent at 0~100 cm among different treatments in 2017 (Figure 4). PS treatment exhibited higher soil water storage capacity after irrigation and/or rainfall due to the loose topsoil and the destroyed plow pan, which was more conducive to the deep movement of soil moisture and root water uptake as compared with PR and PZ treatment. Soil evaporation dominated most of the water consumption during the seedling stage and wintering period (128 days with total rainfall of 118.2 mm and maximum rainfall of 24 mm) and the soil water storage of PS was insignificantly higher than PR and PZ treatment. Compared to PZ treatment, soil water storage of PS treatment increased apparently by 13.41% and 19.48% ($p < 0.05$) after irrigating on 16 Mar and 29 Apr, respectively, and the corresponding amplification for PR treatment was 5.86% and 8.11% ($p > 0.05$).

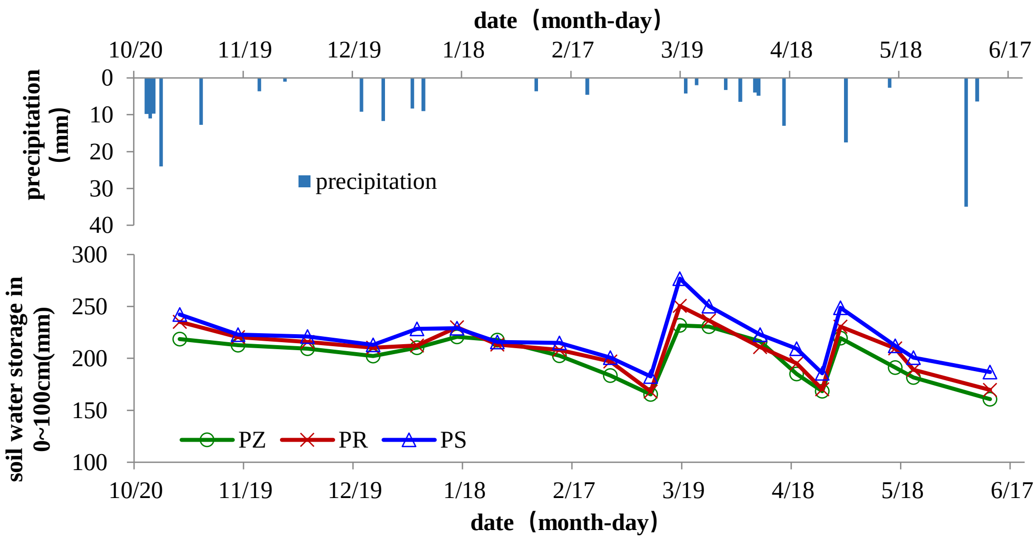

Figure 4. Changes of soil water storage at 0~100 cm under different tillage methods (2017). PZ, no tillage; PR, rotary tillage; PS, subsoiling.

3.2.2. Effect of Tillage Methods on Water Consumption Process of Winter Wheat

For calculation of water consumption of winter wheat in different stages by water balance method, the results are shown in Table 6. The two-year studies showed that the water consumption of winter wheat under PS was the largest in the whole growth period, followed by that under PR treatment, while under PZ treatment was the smallest. The average water consumption of each treatment in the two years was 388.96 mm under PS treatment, 376.81 mm under PR treatment, and 344.67 mm under PZ treatment, respectively. The water consumption intensity of PR treatment at seedling stage is the largest, which is mainly due to the small transpiration of winter wheat plants, and the water consumption is mainly soil evaporation. PR treatment makes the soil above the plow pan looser, which is beneficial to soil evaporation, whereas PS and PZ treatments combined with straw mulching can effectively inhibit soil evaporation and reduce water consumption at this stage. With the vigorous growth of plants, the leaf area index (LAI) and canopy coverage of winter wheat increased gradually at the beginning of the regeneration period, and the water consumption turned mainly to transpiration. Simultaneously, PS treatment accumulated a certain amount of soil moisture in the deep layer and, hence, the water consumption intensity was greater than that of the other two treatments from regeneration stage to heading stage.

Table 6. Water consumption (mm) and intensity (mm·d^{-1}) of each growing stage under different tillage methods.

			Growth stage of winter wheat						
Year	**Treatments**	**Item**	**Seedling Stage (69 d)**	**Wintering Stage (59 d)**	**Regeneration Stage (32 d)**	**Jointing Stage (28 d)**	**Heading Stage (12 d)**	**Filling Stage (35 d)**	**The Whole Growth Seasons (235 d)**
2017	PZ	WC	60.06	50.22	38.86	62.74	50.94	83.97	346.79
		WCI	0.87	0.85	1.21	2.24	4.25	2.40	1.48
	PR	WC	78.05	53.43	40.64	65.87	55.64	85.16	378.79
		WCI	1.13	0.91	1.27	2.35	4.64	2.43	1.61
	PS	WC	69.96	43.38	51.56	79.69	59.36	88.69	392.64
		WCI	1.01	0.74	1.61	2.85	4.95	2.53	1.67
Year	**Treatment**	**Item**	**Seedling Stage (63 d)**	**Wintering Stage (66 d)**	**Regeneration Stage (26 d)**	**Jointing Stage (30 d)**	**Heading Stage (13 d)**	**Filling Stage (29 d)**	**The Whole Growth Seasons (227 d)**
2018	PZ	WC	42.62	51.55	35.19	82.45	48.37	82.36	342.54
		WCI	0.68	0.78	1.35	2.75	3.72	2.84	1.51
	PR	WC	69.32	55.64	35.7	80.61	52.85	80.7	374.82
		WCI	1.10	0.84	1.37	2.69	4.07	2.78	1.65
	PS	WC	51.12	49.95	43.21	94.65	65.33	85.01	385.27
		WCI	0.81	0.70	1.66	3.16	5.03	2.93	1.70

PZ, no tillage; PR, rotary tillage; PS, subsoiling. WC, water consumption; WCI, water consumption intensity. Mean value ± SD.

3.3. Effect of Tillage Methods on Grain Yield and WUE of Winter Wheat

Subsoiling treatment can significantly improve the yield and water use efficiency of winter wheat (Table 7). Grain yield of PS treatment increased by 38.10% ($p < 0.05$) and 34.48% ($p < 0.05$) compared with PZ treatment in 2017 and 2018, respectively. The amplification of grain yield for PR was 21.98% (2017, $p > 0.05$) and 19.32% (2018, $p > 0.05$) compared with PZ treatment. The WUE of PS treatment increased by 21.96% ($p < 0.05$) and 19.57% ($p < 0.05$) compared with PZ treatment in 2017 and 2018, respectively. The amplification of WUE for PR was 11.67% (2017, $p > 0.05$) and 9.05% (2018, $p > 0.05$) compared with PZ treatment. The results showed that in the Xinxiang area of Henan Province, subsoiling combined with straw returning treatment could better coordinate the relationship between water consumption and yield, significantly improve the yield and water use efficiency, and realize the purpose of water saving and yield increase of winter wheat.

Table 7. Grain yield and water use efficiency of winter wheat under different tillage methods.

Year	Treatments	Grain Yield (kg·ha)	WC (mm)	WUE ($kg \cdot ha^{-1} \cdot mm^{-1}$)
2017	PZ	8190 ± 609.55 [b]	346.79 ± 13.43 [b]	23.62 ± 0.54 [b]
	PR	9990 ± 558.53 [ab]	378.79 ± 10.09 [a]	26.37 ± 1.20 [ab]
	PS	11310 ± 650.90 [a]	392.64 ± 13.53 [a]	28.81 ± 0.86 [a]
2018	PZ	8094 ± 760.56 [b]	342.54 ± 19.80 [b]	23.63 ± 1.48 [b]
	PR	9658 ± 661.99 [ab]	374.82 ± 9.63 [a]	25.77 ± 0.60 [ab]
	PS	10085 ± 647.63 [a]	385.27 ± 10.37 [a]	28.25 ± 0.97 [a]

PZ, no tillage; PR, rotary tillage; PS, subsoiling. WC, water consumption; WUE, water use efficiency. Values in the same column with different letters differ significantly ($p < 0.05$). Mean value ± SD.

4. Discussions

4.1. Effect of Subsoiling on Plough Layer Structure

Soil bulk density is a characteristic parameter reflecting soil porosity, and soil compaction is used to evaluate soil compactness and looseness. Both are important indicators to measure soil fertility and cultivated land quality [23], and their sizes directly affect soil permeability, water and nutrient transmission and utilization, and further affect crop growth and yield formation [24]. Bai et al. [25] showed that the average soil bulk density of no-tillage/subsoiling rotational tillage treatment was 3.6% lower than that of continuous tillage treatment, and the average soil porosity, field capacity, and soil organic matter content were increased by 4.4%, 11.6%, and 6.9%, respectively. Zhao et al. [8] showed that subsoiling significantly reduced soil compaction and soil three-phase ratio. Subsoiling before winter wheat sowing significantly reduced soil bulk density (2.53–3.85%) in 0–40 cm layer of subsequent summer maize at seedling stage and jointing stage, increased soil porosity (2.11–3.67%), and reduced soil compactness (22.26–37.76%) in 20–40 cm soil layer at jointing stage, which created suitable soil environment conditions for high yield of crops [15]. Our study also found that subsoiling and rotary tillage significantly reduced soil bulk density by 8.06% and 6.28% (2-year average) and increased soil porosity by 11.38% and 8.89% (2-year average) in 0–40 cm soil layer compared with no-tillage, respectively. Decreasing range of compaction for subsoiling were 40.85% and 56.96% (2-year average) in 0–40 cm soil layer compared with rotary tillage and no-tillage, respectively. The results indicated that reasonable tillage measures can optimize soil physical properties and improve the quality of cultivated land. Subsoiling technology uses shovels to loosen the soil without turning the topsoil, effectively breaking the hard plow pan, reducing soil bulk density and compactness to optimizing physical structure of cultivated horizon [26], improving soil porosity and perviousness, increasing soil water storage and moisture conservation capacity, and promoting soil fertility and continuous yield increase of crops [27].

Tillage methods and straw returning are the main driving factors for soil organic carbon turnover in farmland [28]. Reasonable tillage measures combined with crop straw returning can effectively improve soil organic carbon content. Soil organic carbon content not only reflects the quality of soil texture, but also directly affects the level of crop yield, as well as one of the important ways to mitigate the greenhouse effect. In recent years, some studies have considered that rotary tillage has great disturbance on topsoil, increasing soil organic carbon decomposition and reducing soil organic carbon content. Inversely, no tillage and subsoiling had little disturbance on soil, which reduced the chance of deep soil contacting air and increased the content of soil organic carbon [29–31]. A few researchers believed that the organic carbon in soil under no-tillage treatment was mainly concentrated in the topsoil and decreased sharply with the deepening of soil layer [32,33]. This study showed that, compared with no-tillage treatment, subsoiling significantly increased the soil organic carbon content in the cultivated horizon at 20–30 cm and 30–40 cm by 14.70–24.73%, whereas rotary tillage treatment reduced soil organic carbon content in 0–40 cm to varying degrees (especially in 0–10 cm), which was consistent with previous research results [29,30,32]. Therefore, adoption of subsoiling combined with straw returning could significantly improve the organic carbon content of cultivated horizon in Northern Henan and had a positive effect on the promotion of cultivated land quality.

4.2. Effects of Subsoiling on Soil Water Consumption, Yield and Water Use Efficiency of Winter Wheat

Tillage methods change the structure of soil cultivated horizon, reduce soil bulk density, improve soil porosity, reduce soil compaction, and further change the soil moisture storage and supply capacity. Therefore, improving the water use efficiency by optimizing tillage methods is one of the key cultivation techniques for water saving and high yield of winter wheat in the region. In the present study, the soil water storage capacity of subsoiling treatment was significantly higher than that of rotary tillage and no-tillage treatment after irrigation or rainfall. Subsoiling treatment loosened the topsoil and broke the plow pan, which was more conducive to the water movement to the deep layer and improved the absorption of soil moisture by crop root [34,35]. In addition, subsoiling treatment could inhibit ineffective water evaporation of surface soil at seedling stage, effectively provide sufficient water for root growth and development at mid-growth stage, and meet the water requirement for plant transpiration, which laid a foundation for grain filling and yield improvement at late growth stage [19]. Accordingly, as a suitable tillage method, subsoiling combined with straw returning is conducive to the rational construction of soil tillage layer and can significantly improve grain yield and water use efficiency of winter wheat, which was also proved by the investigation of Zhao et al. [36] and Zhang et al. [6] in the North China Plain. However, the promotion and application of subsoiling technology is still limited by the objective or subjective factors such as degree of land leveling, area size, soil type, and tractor operator's ability. In addition, this study was carried out under the specific plough layer structure and further investigation needs to be carried out in different regions and/or varied climatic conditions.

5. Conclusions

Subsoiling combined with straw returning can effectively break the plow pan, significantly reduce soil compaction, improve soil porosity, and reduce soil bulk density (especially in 20–40 cm). Subsoiling significantly increased soil organic carbon content by 14.70–24.73% in 20–30 cm and 30–40 cm compared with no tillage treatment, whereas rotary tillage reduced soil organic carbon content in 0–40 cm to varying degrees (especially in 0–10 cm). Subsoiling is more conducive to the water movement to the deep layer after irrigation or rainfall, which increases the deep soil water content and provides a favorable soil environment for root growth. Subsoiling combined with straw returning can significantly improve grain yield and water use efficiency of winter wheat. Compared with no-tillage treatment, the grain yield and water use efficiency of subsoiling combined with straw returning increased by 34.48–38.10% and 19.57–21.96%, respectively.

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