



Article

No tillage with straw mulching improve yield and water use efficiency in spring wheat (*Triticum Aestivum* L.) on the semi-arid Loess Plateau of China

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Abstract: Water scarcity is the most important constraint to spring wheat production in the Loess Plateau region of China. Improving the **WUE (water use efficiency)** of crops is the most effective way to increase yields in the region. The objective of this research was to investigate the effects of different stubble and management practices, including conventional tillage (CT), no tillage with straw mulching (NTS), no tillage with no straw mulching (NT), and conventional tillage with straw mulching (TS), on soil moisture and nutrition, dry matter growth, accumulation of osmotic substances, dynamic changes in antioxidant enzymes, and grain yield components, thus exploring the mechanisms of different tillage measures on grain yield of spring wheat (*Triticum aestivum* L.). The year 2020 was a wet year (annual precipitation of 524 mm and 292 mm of the growing season); the years 2021 and 2022 were dry years (286 and 169 mm of annual precipitation and 247 and 122 mm of the growing season, respectively). NTS significantly improved soil moisture and nutrient. The maximum increase of 18.86–62.07% was observed in NTS and TS treatments compared to CT in 0–30 cm soil layer at seeding stage. The cross-regulation substance was much lower in 2020 than in 2021 and 2022. Compared to CT, proline content was significantly increased by 15.80% in NTS in 2020. However, proline content in the NTS treatment was significantly higher than 100% compared to CT in 2021 and 2022. At flowering and filling stages, the MDA (malondialdehyde) content decreases substantially in 2020 compared to 2021 and 2022. MDA content was significantly reduced by 13.72–58.55% and CAT (catalase) and POD (peroxidase) content were significantly increased by 4.01–58.55% in NTS and TS treatments compared to CT in three years. Total dry matter and grain yield were higher in 2020 relative to 2021 and 2022. On average, compared to CT, NTS maintained the highest dry matter accumulation throughout the reproductive period, with an increase of 10.47% to 73.33% in 2020–2022. Yields were significantly higher in the NTS and TS treatments compared to the CT by 13.2–24.28% in the three

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44 years. It is concluded that especially in drought years, NTS improves
45 yields by improving the accumulation of soil moisture, nutrients and
46 cross-regulation substance, activating the antioxidant enzyme system in
47 spring wheat and increasing water use efficiency.

48 **Key words:** spring wheat (*Triticum aestivum* L.); tillage measures; cross-
49 regulation substance; antioxidant enzyme system; WUE (water use
50 efficiency);



1. Introduction

The Loess Plateau is an important grain-producing region in China, however, it is severely affected by soil erosion and other environmental factors^[1]. Wheat (*Triticum aestivum* L.) produces about a quarter of the world's food and feeds nearly one-fifth of the world's population. It is considered one of the world's most important food crops^[2], as well as a major food crop in the region. The low and concentrated rainfall and arid climate in the region limit the development of agriculture^[3,4]. The growth of spring wheat in the region is dependent on erratic precipitation and conservation agriculture^[5,6] is considered a reliable agricultural management practice in the region. The three most central conservation tillage measures are reduce, no-till, and organic straw mulching^[7]. Some studies have shown that conservation tillage can suppress weed growth^[8], reduce wind erosion^[9], improve the physical properties of the soil^[10] and increase the effective use of rainwater^[11,12], thus ensuring crop yields. The application of conservation measures on the Loess Plateau can bring crops close to their potential yield^[13,14]. Conservation tillage can improve precipitation use efficiency (PUE), which in turn improves the water use efficiency (WUE) of crops and increases yields. However, the magnitude of crop yield increases depends not only on external rainfall, but also on climatic conditions, soil environment and crop stress tolerance. Understanding the external environmental and physiological mechanisms regulating crop growth and yield under these conditions has significant implications for food security^[14].

The final yield formation of a crop depends on the accumulation of dry matter mass during the reproductive process. It has been shown that conservation tillage reduces soil bulk^[15], increases soil water content^[16,17], increases the effectiveness of water and nutrients in the soil^[18,19], and thus increases dry matter accumulation. NTS significantly increased spike number and spike grain number, thus significantly increasing wheat yield^[20,21]. However, it has also been suggested that NTS significantly reduces dry matter accumulation in wheat^[22]. No-till reduced yield by 9.5% compared to conventional tillage^[23]. No-till reduces the number of ears and thousand grain weight, thus significantly reducing yields^[24,25]. The results of studies on the effects of conservation tillage practices on crop growth and yield vary, depending on the local climate and the number of years that conservation tillage has been applied.

A few studies have shown that conservation tillage can increase the soluble protein content, peroxidase (POD) activity, and catalase (CAT) activity of wheat leaves and reduce malondialdehyde (MDA) content to slow down the aging process and improve wheat yield^[26,27]. However, the process of dynamic influence on crop growth processes with this type index of scavenging reactive oxygen species under conservation tillage



has been rarely reported. Scholars agree that crop growth and eventual yield formation are influenced by hormones and enzymes in the crop, especially the regulation of stress tolerance factors^[28,29]. Ensuring the balance of reactive oxygen species in the plant is the basis for the maintenance of normal plant growth^[30-33]. Crops usually respond to drought-induced oxidative stress by increasing the content of antioxidant enzymes^[34,35]. Proline, soluble protein content, CAT (catalase) and POD (peroxidase) are helpful to maintain the balance of reactive oxygen species and improve the resistance of crops^[36,37]; the rate of MDA accumulation in the plant can effectively reflect the strength of the plant's tissue scavenging ability of free radicals. The higher the MDA content in the crop, the greater the damage^[38,39]. It has been shown that drought stress can effectively induce the hydrogen peroxide scavenging system^[40]. CAT can directly break down H_2O_2 into molecular oxygen and water and POD can further scavenge hydrogen peroxide (H_2O_2) by oxidizing the substrate^[41]. This promotes crop growth and eventual yield formation.

The implementation of conservation agriculture in arid areas has been widely demonstrated to improve crop yields. Although the growth, yield, and drought tolerance of wheat have also been extensively studied, the dynamic changes of antioxidant enzyme systems and the accumulation of cross-regulation substance in relation to crop growth under conservation tillage conditions in arid regions have been little studied. Therefore, in this study, we investigated the relationship between changes in physiological indicators and growth and yield of spring wheat by studying the dynamic changes in growth and antioxidant enzymes and the accumulation of cross-regulation substance under four different tillage measures.



2. Materials and methods

2.1. Site description

The trial site is located at the Rainfed Agricultural Experimental Station (35°28 'N, 104°44 'E) in Lijiabao Town, Dingxi City, Gansu Province, China. The soil and plant samples taken in this study in 2020-2022 were taken from the long-term locational conservation tillage experiment established in 2001. The test site belongs to the arid region of the Loess Plateau with an average altitude of 2000 m and a frost-free period of 140 days. Test land is Calcaric Cambisol^[42], medium and low fertility. The annual cumulative temperature > 10 °C is 2240 °C; the annual radiation is radiated from 5930 m MJ⁻² and the sunshine 2480 h. The precipitation during the growth stage (March - July) in 2020 - 2022 was 291.6, 168.6, and 121.9 mm, respectively. The physicochemical properties of the soil during 2020-2022 were shown in Table 1. The specific precipitation situation is shown in Figure 1.

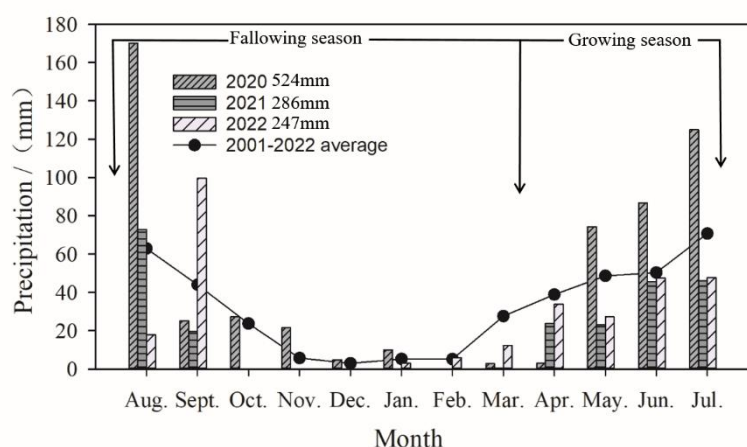


Figure 1 Precipitation of the experimental area (2020-2022)

2.2. Experiment design

The experiment was designed with four treatments, three replications, and a double sequence rotation cropping pattern of spring wheat and peas with interannual rotation of the two crops. The spring wheat and pea varieties are "Dingxi 40" and "Lvning 2", respectively. The seeding rate was 187.5 kg ha⁻¹ for spring wheat in rows spaced 20 cm apart and 180 kg ha⁻¹ for peas in rows spaced 24 cm apart. Calcium superphosphate (105 kg P₂O₅ ha⁻¹ for wheat and peas) and urea (105 and 20 kg N ha⁻¹ for wheat and peas, respectively) were applied to the soil with the seeds at planting. Each experimental plot was randomly distributed, and each plot was 20 × 4 m = 80 m². All samples for this study were collected in the spring wheat field. The treatments and the specific operations were CT (conventional tillage with no straw);



NTS (no-tillage with straw mulching); and NT (no-tillage with no straw mulching); TS (conventional tillage with straw incorporated). Field management and treatment specific treatment measures are described by Huang et al. [43]. Manual weeding during the crop-growing period and herbicides during the fallow period.

2.3. Sampling and measurements

2.3.1. Soil Physical and chemical properties

Soil moisture content was determined using the drying method^[44] in the 0-5, -10 and 10-30 cm soil layers at each fertility period of spring wheat, and the soil moisture content in the 30-50, 50-80, 80-110cm soil layers per plot was determined using a time-domain reflectance soil moisture sensor (TRIME-PICO, IPH/T3, IMKO GmbH, Ettlingen, Germany). Soil physical and chemical properties were sampled before sowing for the period 2020-2022. Soil moisture content in the 0-5, 5-10 and 10-30 cm soil layers was determined using the ring-knife method^[44], with the 0-30 cm soil layer as its mean value. In each plot, samples were taken in the 0-5, -10 and 10-30 cm soil layers, brought back to the laboratory, shade dried, ground finely through a 2.0 mm sieve and measured. Soil total nitrogen content was determined by the method of Semimicro, Kjeldahl. et al., using concentrated sulfuric acid and a catalyst, followed by a fully automatic Kjeldahl nitrogen tester (Model A1225, Thmorgan, Germany)^[45]. And by Cavagnaro, T. et al. [46] for the determination of soil nitrate nitrogen. The effective phosphorus content of the soil was determined by the Olsen method^[47]; it was determined by the 1M NH₄Ac leaching-flame photometric method (A3AFG-00 Atomic Absorption Spectrophotometry, Beijing Spectrum Analysis).

2.3.2 Antioxidant enzymes and cross-regulation substance

Samples were taken at the seedling, jointing, heading, flowering and filling stages of spring wheat in 2020-2022. Fifteen spring wheat leaves were randomly taken in each plot, wrapped in aluminum foil and immediately placed in a bubble box containing liquid nitrogen, which was brought back to the laboratory and transferred to a -80 °C refrigerator for measurement. Proline was determined by the acidic ninhydrin method^[48]; soluble protein content was determined by the Komass Brilliant Blue method^[48]; CAT was determined according to Sun^[49]; POD was determined according to the method described by Rahnamal and Ebrahmzdeh^[50]. MDA content was determined by the method of Sun & Hu^[51].

2.3.3. Dry matter accumulation, grain yield and yield components

Whole plant samples were taken at wheat seeding, jointing, heading, flowering, and filling and grouped according to the experimental plots. Five plants were randomly measured from each plot, and each plant was repeated three times. The tissue



was placed in an oven, dried at 105 °C for 30 minutes, dried at 75 °C to constant weight, and then weighed. At maturity, each plot's edges (0.5 m) were removed, and all remaining plots were harvested by hand with a sickle, dried and threshed using a thresher, and yielded. During harvesting, we randomly select three rows in each plot and determine the effective number of ears per unit area with a row spacing of 50 cm. At the same time, 20 wheat plants were randomly selected in each plot, and the number of effective tillers, the number of grains per ear, and the thousand-grain weight were counted.

2.3.4 Statistical analysis

The analysis of variance (ANOVA) test was used to evaluate soil moisture content, wheat dry matter accumulation, and cross-regulation substance, activating the antioxidant enzyme system and SPSS 19.0 (Company, Chicago, USA) statistical software was used to detect differences among treatments at the 0.05 significant level with the LSD test. Statistical analysis and data graphing were performed with Excel 16.0 and SigmaPlot 14.0, respectively.



3. Results.

3.1 Soil physical properties and nutrient

Different tillage practices had significant effects on soil physicochemical properties (Table 1). Soil bulk density and pH varied between years, but overall showed the highest in CT and the lowest in NTS. In 2020, the soil Total N content of each treatment showed: $NT > NTS \approx CT > TS$; in 2021 and 2022, it showed the highest in NTS treatment and the lowest in the CT treatment. In 2020–2022, the soil NO_3 -N content was significantly higher in the NTS and NT than in CT, and there was no significant difference in soil available P and available K content among the treatments in the three years.

3.2 Precipitation and soil water content

The precipitation in 2020 was 524 mm, which is higher than the multi-year average precipitation and was a water-abundant year (Figure 1). However, the precipitation was concentrated in May–July, and the precipitation in the early stage of spring wheat growth stage was lower than the multi-year average precipitation. 2021 and 2022 were drought years with precipitation lower than the multi-year average precipitation, and the precipitation in the whole growth period was much lower than the multi-year average precipitation.

Soil moisture content increased with increasing soil depth (Figure 2). The water content of each soil layer was affected by interannual and tillage treatments as well as the depth of the soil layer. At the seeding stage, NTS and TS water content significantly increased by 46.27%, 18.86% and 62.07%, 30.09% in 0–5 and 5–10 cm soil layers, respectively, in 2020 compared to CT. In 2021, NTS significantly increased by 12.01% compared to CT in 10–30 cm soil layer; NTS, TS, and NT significantly increased by 8.77–18.83% in 30–50 cm soil layer compared to CT. At the jointing stage, in the 5–10 cm soil layer, NTS treatment significantly increased 13.77% and 15.69% compared to CT in 2020 and 2021, respectively, and there was no significant difference in 2022. At heading stage, NTS treatment was significantly lower than CT by 40.72% in 2021 in the 30–50 cm soil layer; however, there were no significant differences among treatments in other soil layers. At the flowering and filling stage, soil water content was significantly higher in 2020 than in 2021 and 2022 because of significantly higher precipitation at flowering in 2020. In the 0–5 cm soil layer at flowering stage, NTS treatment was significantly higher than CT by 11.27% and 12.54% in 2020 and 2022, respectively. At filling stage, in the 0–30 cm soil layer, NTS was significantly higher than CT by 35.54% in 2020 in the 0–5 cm soil layer; in 2021, NTS treatment had the highest soil water content in the 30–50 cm soil layer, which was significantly higher than CT by 12.5%, and there was no significant difference among treatments in 2022. The overall soil water content was more influenced by natural precipitation than tillage measures. In the



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early growth stage, the NTS and TS treatments in the shallow soil layer can ensure higher soil water content for crop uptake and utilization, which play a key role in the pre-development and dry matter growth of spring wheat.

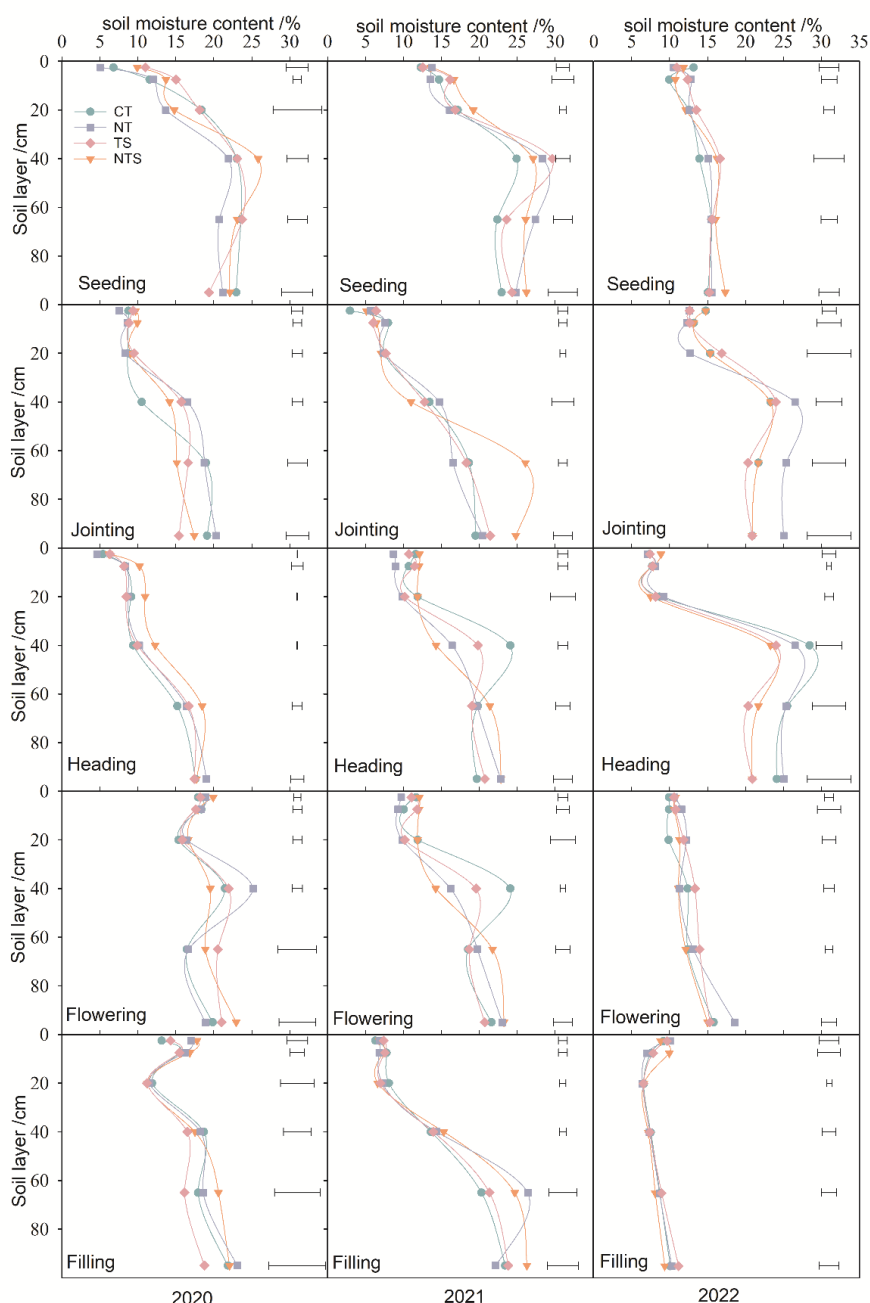


Figure 2 Soil water content at Seeding, jointing, heading, flowering, and filling stages with the different tillage and stubble management practices (CT; NTS; NT; TS) in 2020 - 2022; Bars are LSD at $P < 0.05$. Same as below.

285

Table 1 Soil physical and nutrient in the field during 2020–2022

Years	Treatments	Bulk density (Mg m ⁻³)	pH	Total N (g kg ⁻¹)	NO ₃ ⁻ -N (g kg ⁻¹)	Available P (mg kg ⁻¹)	Available K (mg kg ⁻¹)
2020	CT	1.28±0.02a	8.34±0.02a	0.87±0.02ab	24.17±2.80b	12.20±2.67a	322.07±48.30a
	NTS	1.19±0.03b	8.25±0.03b	0.90±0.03ab	28.63±0.65a	13.00±2.82a	327.57±43.95a
	NT	1.27±0.04a	8.31±0.03a	0.91±0.01a	28.23±0.53a	12.77±2.56a	334.53±37.74a
	TS	1.26±0.04ab	8.34±0.02a	0.86±0.01b	24.23±2.15b	11.37±3.04a	323.03±21.89a
2021	CT	1.27±0.01a	8.34±0.02a	0.86±0.01c	24.33±1.82b	10.63±3.83a	314.80±39.92a
	NTS	1.17±0.02c	8.25±0.02b	0.94±0.01a	28.03±1.41a	12.17±3.80a	333.17±37.07a
	NT	1.21±0.03bc	8.32±0.03a	0.91±0.01b	27.30±1.65a	11.30±4.45a	323.07±45.89a
	TS	1.22±0.02ab	8.33±0.02a	0.87±0.01c	23.77±0.71b	10.90±3.94a	318.67±40.29a
2022	CT	1.30±0.01a	8.33±0.01a	0.85±0.02b	24.47±1.96b	10.67±3.68a	315.47±42.56a
	NTS	1.17±0.02b	8.24±0.02b	0.93±0.01a	28.40±0.28a	12.30±4.17a	330.37±41.17a
	NT	1.26±0.04a	8.28±0.02b	0.87±0.01b	27.53±0.88ab	10.87±3.84	313.67±57.03a
	TS	1.20±0.01b	8.26±0.02b	0.86±0.02b	24.80±2.20b	10.00±3.94a	307.53±51.45a

Within a column for a given year, means followed by different letters are significantly different ($P \leq 0.05$). Same as below.



3.3 Antioxidant enzymes and cross-regulation substance

The proline content in spring wheat was much greater in 2021 and 2022 than in 2020 (Fig. 3). In 2020, the NTS treatment showed a 29.70–64.90% increase compared to the CT at the jointing, heading and filling stages. At the flowering stage, the NTS, NT and TS treatments significantly increased by 15.80, 25.61 and 64.03%, respectively, compared to the CT. At the seeding stage in 2021, NTS, NT, and TS treatments significantly improved 62.20–153.66 % compared to CT.

Overall, the soluble protein content was lower in 2020 than in 2021 and 2022. The soluble protein content of spring wheat reached the highest at flowering. In 2020, NTS treatment, NT, and TS treatments were significantly higher by 1.27–14.12% compared to the CT at the flowering and filling stages. In 2021, NTS and TS treatments were significantly lower by 0.56 and 0.87%, respectively, at the flowering stage compared to CT. In 2022, NTS, NT and TS treatments improved by 1.06–4.37% compared to CT at seedling stage. At the flowering stage, NTS and TS treatments were significantly reduced by 0.83 and 0.29%, respectively, compared to CT; NT treatment was significantly improved by 0.57%.

MDA levels were lower in 2020 than in 2021 and 2022. In 2020, the MDA content of NTS treatment showed the highest reduction of 21.00 and 14.17% compared to the CT at the flowering and filling stage, respectively. There were no significant differences between CT, NT and TS treatments. In 2021, the NTS treatment showed a significant reduction of 20.94 and 17.66% compared to CT at the seeding and flowering stage, respectively. The NTS, TS and NT treatments were significantly lower than CT by 13.72–30.56%.

The overall CAT level in 2020 was lower than in 2021 and 2022. In 2020, compared to CT, the CAT content of NT and TS treatments were significantly increased by 20.80 and 3.98%, respectively. At heading and flowering stage in 2021, NTS and TS treatments significantly increase 17.91–58.55% compared to CT. In 2022 at heading and flowering stages, NTS treatment increase by 14.50 and 19.61%, respectively, compared to the CT.

The overall POD level in 2020 was lower than in 2021 and 2022. In 2020, spring wheat POD activity NTS>TS>NT>CT. 73.48 and 62.14% were significantly higher in NTS treatment compared to CT at jointing and heading stage, respectively. During the whole reproductive period of spring wheat in 2021, the increase of NTS treatment over CT ranged from 4.01–49.71%; TS increased from 1.67–10.71%. At the flowering stage in 2022, NTS and TS treatments significantly decreased by 14.1 and 21.8%, respectively, compared to CT, and significantly increased by 7.00 and 0.29%, respectively, at the filling stage.

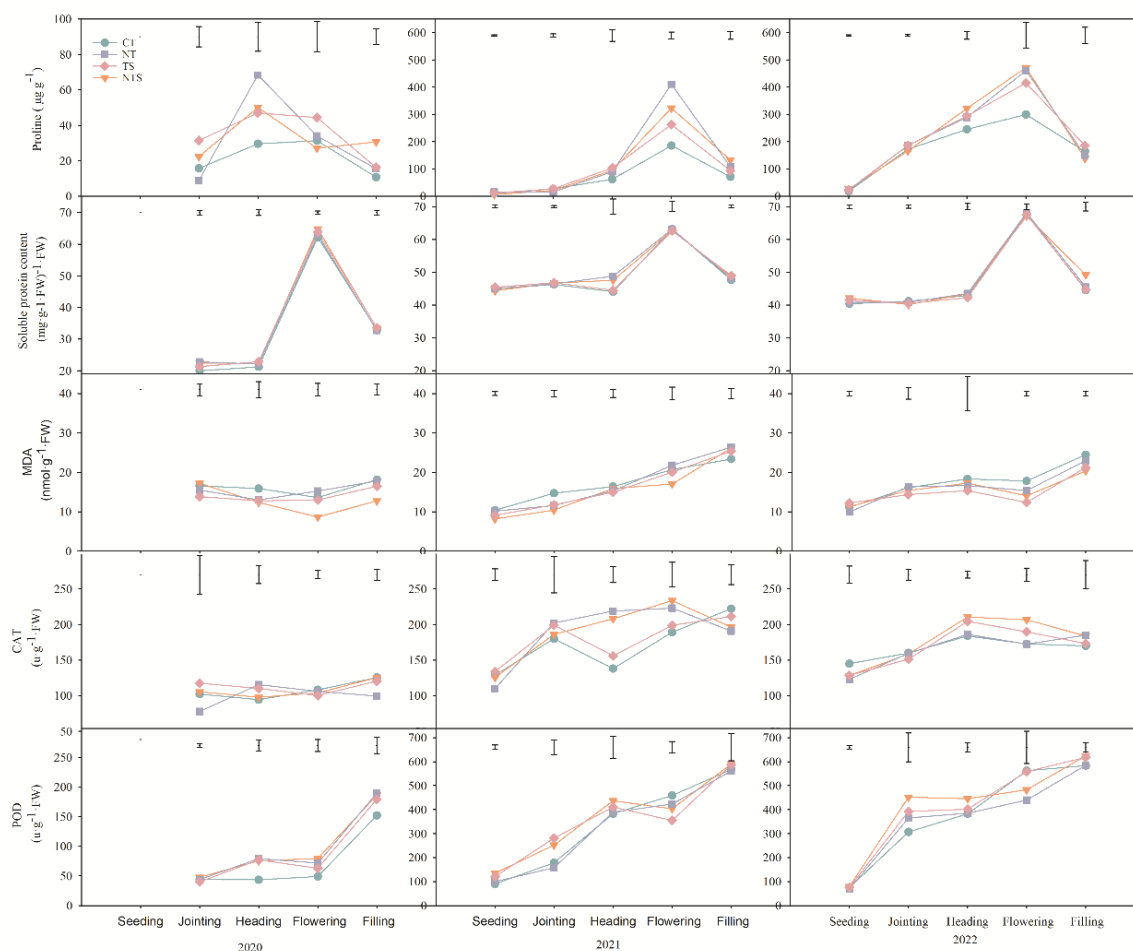


Figure 3 Antioxidant enzymes and cross-regulation substance of spring wheat at seeding, jointing, heading, flowering, and filling stages with the different tillage and stubble management practices (CT; NTS; NT; TS) in 2020–2022.

3.4 Biomass *accsumption*, grain yield and yield components

Tillage measures significantly affected wheat dry matter growth (Figure 4). Total biomass in 2020 was higher than in 2021 and 2022. And in every growth period, the amount of wheat dry matter in 2020 was generally higher than in 2021 and 2022. In the aboveground dry matter accumulation of wheat, NTS grows best, with an average increase of 11.33%–38.97% compared with CT in 2020; and an increase of 10.47%–73.33% in 2021 and 2022. During 2020–2022, NTS increased 38.97%–73.37% at the heading stages, respectively, compared with CT. In the filling stage in 2020, NTS was significantly increased by 51.55% compared with CT, and NT and TS were also significantly increased by 8.44% and 43.55% compared with CT, respectively; in 2021, there was no significant difference among the treatments, and the root dry matter quality

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of NTS was the highest by 2.14% compared with CT. In 3 years, the NTS treatment always maintained the highest biomass compared to the other treatments.

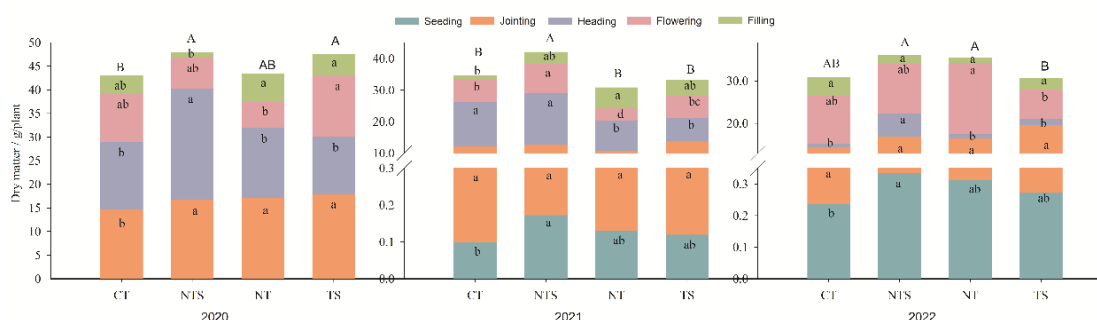


Figure 4 Effect of different stubble and management practices on dry matter accumulation in spring wheat at seeding, jointing, heading, flowering, and filling stages. Means followed by different letters in a column are significantly different ($p \leq 0.05$), with lowercase letters indicating significant differences between stages; uppercase letters indicate significant differences overall.

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The highest yield was NTS in 2020–2022 (Table 2). The yield was $NTS > TS > NT > CT$. NTS and TS significantly increased yield by 13.20–24.28% compared with CT in 2020–2022. Production in 2020 is higher than in 2021 and 2022, but NTS handles a higher increase than CT with the lowest in 2020. NTS improved wheat yield through enhanced wheat spikes per area and grain per spike. Among them, wheat spikes per area in the NTS increased by about 40% compared with the CT during 2020 to 2022. The NTS treatment had the highest WUE in the 3 years, which was significantly higher than the other treatments.

Table 2 Effect of different tillage practices on yield, yield components and WUE (water use efficiency) of spring wheat

Years	Treatments	Spikes per area m^{-2}	Grain per spike	TGW (1000-grains weight)	Grain Yield	WUE ($kg\ hm^{-2}\ mm^{-1}$)
2020	CT	453.20b	47.29ab	36.60b	2117.95b	7.11b
	NTS	606.80a	53.89a	40.20a	2618.73a	8.53a
	NT	530.00b	46.64ab	38.76ab	2185.05b	6.95b
	TS	466.80b	47.96b	36.72b	2397.5ab	7.47ab
2021	CT	373.20b	31.93bc	31.37b	1099.65b	4.08c
	NTS	506.88a	37.30a	34.57a	1366.60a	7.18a
	NT	374.94b	27.25c	29.70b	1197.59ab	4.88bc
	TS	448.66a	35.42ab	31.40b	1331.96a	5.18bc
2022	CT	366.33b	29.37a	32.50a	1103.90c	6.49b
	NTS	583.00a	32.88a	33.26a	1662.92a	9.14a



NT	406.00b	34.97a	31.35a	1201.85bc	7.05b
TS	424.33b	37.08a	30.26a	1371.11b	7.87ab

3.5 Correlations

In this study, principal component analysis was done for soil physical and chemical property characteristics (factors that contradict other physicochemical factors in terms of capacity excluded) and antioxidant enzymes and cross-regulation substance (MDA contradictory to other factors excluded), respectively, as shown in the following table.

Table 3 Principal component scores for soil physical and chemical properties under different tillage practices

Treatment	F ₁	F ₂	F ₃	F ₄	F ₅	F ₆	F
CT	-1.81	0.623	0.353	-0.93	0.013	0.837	-1.123b
NTS	2.243	-0.853	0.377	0.213	1.03	-1.337	1.190a
NT	0.317	-0.267	0.38	0.443	-0.96	-0.773	-0.273ab
TS	-0.75	0.497	-1.113	0.267	-0.087	1.277	0.207ab

Note: F₁, the first principal component; F₂, second principal component, and so on; F, the synthesis of the principal components. The same below.

The combined scores of NTS, NT and TS treatments were significantly higher than those of CT during the 3-years stages of 2020-2022 (Table 3), with NTS treatment having the highest combined score. This indicates that the other tillage practices can significantly improve the soil physicochemical properties compared to CT, with the NTS treatment performing the best.

Table 4 Principal component scores of antioxidant enzymes and cross-regulation substance under different tillage practices

Treatment	F ₁	F ₂	F ₃	F ₄	F ₅	F ₆	F ₇	F
CT	-5.61	-1.673	1.73	-0.563	-0.377	-0.423	0.15	-1.613c
NTS	5.36	0.64	2.14	-1.113	-0.717	-0.537	-0.083	1.550a
NT	-1.26	3.78	-2.507	-0.057	0.033	-0.543	0.54	-0.060b
TS	1.507	-2.747	-1.363	1.733	1.063	1.503	-0.61	0.130b

From Table 4, it can be seen that the combined scores of antioxidant enzymes and cross-regulation substance were significantly higher in other tillage treatments compared to CT. The NTS treatment had the highest score and the difference between the NT, and TS treatments was not significant. Therefore, the NTS treatment could significantly improve the antioxidant enzymes and cross-regulation substance of spring wheat.

Table 5 Correlation of various antioxidant enzymes and cross-regulation substance with dry matter in spring wheat from 2020 to 2022

Years	Proline	Soluble protein	MDA	CAT	POD
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Seeding stage					
2020	-	-	-	-	-
2021	0.171	-0.329	-.736**	0.01	0.552
2022	-0.046	0.487	-0.34	-0.565	0.321
Jointing stage					
2020	-0.214	0.255	-0.640*	0.041	-0.414
2021	0.005	0.562*	-0.564*	0.027	0.408
2022	-.583*	-0.266	-0.563*	-0.254	0.143
Heading stage					
2020	0.061	0.534*	-0.337	0.571*	0.557*
2021	-0.405	0.052	0.141	-0.078	0.308
2022	.597*	0.24	-0.502	0.196	0.463
Flowering stage					
2020	-0.113	0.418	-0.565*	0.043	0.464
2021	-0.386	-0.159	-0.27	0.118	0.084
2022	.599*	0.244	0.33	-0.216	-0.39
Filling stage					
2020	-0.478	-0.108	-0.527*	0.477	0.144
2021	-0.375	-0.038	-0.076	-0.073	0.046
2022	-0.241	-0.241	-0.579*	-0.438	.585*

The correlation between dry matter and antioxidant enzymes and cross-regulation substance in spring wheat during 2020–2022 (Table 5) showed that proline content was significantly and negatively correlated with dry matter at nodulation and positively correlated with dry matter at heading and flowering. Soluble protein was significantly and positively correlated with dry matter at nodulation and tassel stage and not significantly and negatively correlated with dry matter at the filling stage. MDA content was significantly and negatively correlated with dry matter mass. CAT and POD were positively correlated with dry matter growth in spring wheat.

Table 6 Correlations between soil physical and nutrient, various antioxidant enzymes and cross-regulation substance, yield components, yield and water use efficiency in spring wheat

	Fd	Grains	Spikes	KGW	GY	WUE
Fp	0.576	-0.127	.722**	-0.286	.763**	.697*
Fd	1	0.202	.708**	0.149	.828**	.829**
Grains		1	0.212	0.482	0.173	0.411
Spikes			1	0.157	.732**	.851**
KGW				1	0.068	0.298
GY					1	.918**
WUE						1

Note: Fp, combined factor of soil properties; Fd, combined factor of drought resistance index; Grains, number of spikes; Spikes, number of spikes; KGW, thousand grain weight; BY, biological yield; GY, seed yield; WUE, water use efficiency.



Correlation analysis showed (Table 6) that the combined factors of soil moisture and nutrient were significantly and positively correlated with spike number, grain yield, and water use efficiency. The composite factor of cross-regulation substance and antioxidant enzyme activity factors was significantly and positively correlated with dry matter, spike number, grain yield and water use efficiency of spring wheat. The number of spikes was significantly and positively correlated with grain yield and water use efficiency. Dry matter yield was significantly and positively correlated with yield.



4. Discussion

4.1 No tillage with straw mulching optimizing spring wheat grain yield by improves soil moisture and nutrients

Many studies in the earlier part of this long-term locational experiment showed that the NTS treatment significantly reduced soil bulk density and increased soil nutrient content^[52,53]. After more than 20 years of long-term trials, the NTS treatment soil bulk density remained at the lowest level. Moreover, the NTS treatment had the highest content of total nitrogen, nitrate nitrogen and effective phosphorus in the 0–30 cm soil layer; the pH was lower and more suitable for crop growth and development^[54]. This may be due to the increase in soil organic matter content by microbial decomposition as a result of returning straw to the field, which increases the soil nutrient content^[18]. The application of no-till measures in turn maximizes the protection of soil voids for root growth^[55], reduces the direct impact of rainfall directly on the soil and retains water^[52,56]. The availability of water and nutrients provides the basis for crop dry matter growth and yield improvement, further increasing the amount of return to the field, which creates a good cycle.

High dry matter accumulation during the crop growing period is the basis for high crop yield^[1]. Our study showed that dry matter accumulation was significantly and positively correlated with soil physicochemical properties during the reproductive period of spring wheat. In agreement with the studies of other researchers^[20,21,57], the number of spikes and grains per spike were significantly higher in NTS than in other treatments based on high biomass, which was an important reason for its high yield. However, it has also been shown that NTS can lead to a significant decrease in biomass yield of winter wheat, thus affecting yield^[22,58]. NTS treatments reduce crop yield by an economic coefficient^[59] with economic coefficient Siddique et al.^[60]. This may be due to climatic differences in different agroecological zones and may also vary with the length of time when conservation tillage is implemented^[1,61], which is also related to field management practices. In conclusion, NTS treatment can significantly increase soil nutrient content, dry matter accumulation during the course of crop fertility, spike number and grain number, and thus yield.

4.2 No tillage with straw mulching improves yield in spring wheat by accumulation of cross-regulation substance and activation of antioxidant enzyme system

Drought is one of the most important abiotic factors affecting crop growth and yield^[62]. The osmotic effects induced by drought stress can induce a variety of responses, such as growth inhibition as well as an increase in cellular osmotic potential^[63]. Plant drought tolerance is associated with changes in antioxidant enzymes and the maintenance of H₂O₂ levels. Kukreja et al.^[64] reported the response of water stress to peroxide



activity and superoxide dismutase. Numerous studies on different species have shown that drought stress alters the activity of reactive oxygen species-related enzymes. In this study, we showed that there were significant differences in each drought tolerance index in spring wheat between treatments. We found that NTS treatment significantly increased proline and soluble protein content in spring wheat, delayed the crop senescence process, and increased crop growth time to improve final crop yield. MDA is a very important indicator of drought resistance in crops, and the lower the MDA content, the higher the antioxidant capacity and the greater the drought resistance^[65]. In our study, NTS treatment significantly reduced the MDA content and could delay the process of water loss from the crop, thus improving the drought resistance of the plant. CAT effectively decomposed the high concentration of H₂O₂ in the leaves of wheat seedlings and reduced the damage caused by H₂O₂ to the crop. CAT regulates the level of hydrogen peroxide in plant cells, and different levels of drought stress can affect CAT content^[66]. In addition, POD, which is widely present in different crop tissues, is another enzyme involved in the removal of H₂O₂, and it is also a key enzyme affecting plant growth, development and lignification^[67]. We found that CAT and POD contents in NTS and TS treatments had stable and high levels throughout the reproductive process. The synergistic effect of these key drought tolerance factors effectively scavenged reactive oxygen species in vivo and improved the drought tolerance of the crop. Under stress conditions, drought-tolerant plants tend to have higher POD activity than sensitive plants^[68]. Similar findings were also seen in studies on oilseed rape^[69].

The NTS treatment significantly improved the crop's drought resistance. We performed a correlation analysis between various antioxidant enzymes and cross-regulation substance and dry matter accumulation during the reproductive process, and the results showed that there was a significant positive correlation between drought resistance factors and dry matter accumulation (Table 5). In addition, there was a significant positive correlation between various antioxidant enzymes and cross-regulation substance, yield, and WUE. We have reason to believe that NTS promotes dry matter accumulation and thus yield formation through accumulation of cross-regulation substance and activation of antioxidant enzyme systems.



5. Conclusion

No tillage with straw mulching increased soil moisture content and nutrient content, optimized dry matter accumulation, thus promoting spike and spike grain numbers and ultimately increased yield. In addition, it was shown that NTS significantly accumulation of cross-regulation substance and activation of antioxidant enzyme system, enhance WUE, and prolonged the growth and development of spring wheat, which in turn increased yield. In summary, no tillage with straw mulching improves yield by improving soil moisture, nutrient and accumulation of cross-regulation substance, activation of antioxidant enzyme system of spring wheat and water use efficiency. This conclusion is even more applicable in drought years.



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