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Conservation Tillage Increases Water Use Efficiency of Spring Wheat by Optimizing Water Transfer in a Semi-Arid Environment

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Abstract: Water availability is a major constraint for crop production in semiarid environments. The impact of tillage practices on water potential gradient, water transfer resistance, yield, and water use efficiency (WUE_g) of spring wheat was determined on the western Loess Plateau. Six tillage practices implemented in 2001 and their effects were determined in 2016 and 2017 including conventional tillage with no straw (T), no-till with straw cover (NTS), no-till with no straw (NT), conventional tillage with straw incorporated (TS), conventional tillage with plastic mulch (TP), and no-till with plastic mulch (NTP). No-till with straw cover, TP, and NTP significantly improved soil water potential at the seedling stage by 42, 47, and 57%, respectively; root water potential at the seedling stage by 34, 35, and 51%, respectively; leaf water potential at the seedling stage by 37, 48, and 42%, respectively; tillering stage by 21, 24, and 30%, respectively; jointing stage by 28, 32, and 36%, respectively; and flowering stage by 10, 26, and 16%, respectively, compared to T. These treatments also significantly reduced the soil–leaf water potential gradient at the 0–10 cm soil depth at the seedling stage by 35, 48, and 35%, respectively, and at the 30–50 cm soil depth at flowering by 62, 46, and 65%, respectively, compared to T. Thus, NTS, TP, and NTP reduced soil–leaf water transfer resistance and enhanced transpiration. Compared to T, the NTS, TP, and NTP practices increased biomass yield by 18, 36, and 40%; grain yield by 28, 22, and 24%; and WUE_g by 24, 26, and 24%, respectively. These results demonstrate that no-till with straw mulch and plastic mulching with either no-till or conventional tillage decrease the soil–leaf water potential gradient and soil–leaf water transfer resistance and enhance sustainable intensification of wheat production in semi-arid areas.

Keywords: conservation tillage; water potential gradient; water transfer resistance; transpiration; water use efficiency

1. Introduction

Wheat (*Triticum aestivum* L.) is a major food crop in the world, which plays an important role in ensuring food security [1]. The western Loess Plateau of China is characterized by harsh climatic conditions including frequent spring drought, severe wind erosion, and water erosion [2,3]. Spring wheat is one of the dominant crops in this region, but its growth is restricted by limited and erratic rainfall [4,5]. Thus, yield of spring wheat in this region is far less than potential yield, ranging from 1500 to 3000 kg ha^{-1} [6–8]. Increasing water use efficiency (WUE) is a major goal for advancing sustainable intensification of crop production on the western Loess Plateau, which will have a great impact at local and regional scales [9].

Water use efficiency depends on the amount of water uptake by plants, of which the majority is lost through transpiration [10]. Plant water uptake depends on the free energy of water in plants and water potential in the soil–plant–atmosphere continuum [11]. The lower the water potential of the plant, the stronger the water absorption capacity. Van den Honert [12] found that the transpiration rate was positively correlated with the water potential difference of the leaf–atmosphere system. Yang et al. [13] found that the leaf water potential of maize (*Zea mays* L.) decreased from the lower to upper part of the canopy and that there was relatively large resistance among the different interfaces of water flow in the transmission process. Xerophytes have moderately deep roots and show a rapid drop in leaf water potential with increasing leaf water deficit, which generates a steep water potential gradient in the soil–plant continuum that enhances water uptake by roots [14].

Conservation tillage reduces soil disturbance and retains crop residues on the soil surface [15]. It can effectively reduce wind erosion [16], water erosion [17], and soil bulk density, and enhance soil total porosity and saturated water conductivity [18–21], thereby increasing rainfall infiltration and soil water holding capacity [22,23], reducing soil evaporation, and enhancing crop growth, yield, and WUE [24–26]. No-till with straw cover has been shown to improve grain yield by 13%, and WUE by 7.6% in winter wheat on the Loess Plateau of China [27]. No-till with straw cover has been shown to improve grain yield by 153%, and WUE by 46% in a wheat and maize (*Zea mays* L.) relay-planting system on the Hexi Corridor of northwestern China with a typical temperate arid zone of the continent [28]. Subsoil tillage with 50% chopped straw mulching has been shown to improve grain yield by 5%–7%, and WUE by 51%–52% in maize on the Huang–Huai–Hai valley with a mean annual precipitation of 556.2 mm [29]. Ridge mulched with plastic film has been shown to improve grain yield by 30%, and WUE by 35% in wheat on the Loess Plateau of China [4]. However, the mechanism in which conservation tillage improves water use efficiency from the perspective of water potential gradient is poorly understood. Therefore, the objectives of this study were to assess the effects of different tillage practices on soil, root, and leaf water potential indexes, soil–leaf water transfer resistance, transpiration, yield, and WUE of spring wheat.

2. Materials and Methods

2.1. Experimental Site

This study was conducted in 2016 and 2017 based on a long-term field experiment initiated in 2001. The experiment was at the Rainfed Agricultural Experimental Station (35°28′ N, 104°44′ E, elevation: 1971 m above sea level) of Gansu Agricultural University in Gansu Province in northwestern China, a typical rainfed area on the western Loess Plateau. The area is characterized by a hilly landscape and is prone to soil erosion. The aeolian soil at the experimental site is locally known as Huangmian [30], is a Calcaric Cambisol according to the IUSS Working Group WRB (2015) [31], and is primarily used for annual crop production [32]. This soil has a sandy loam texture with ≥50% sand. Detailed soil physical and water characteristics before sowing in 2001 are presented in Table 1, and detailed procedures for the measurement of indicators in Table 1 are described in Huang et al. [33]. Annual precipitation was 300.2 mm in 2016, 361.4 mm in 2017, and 396.7 mm averaged in the 2001–2015 period (Figure 1). The annual (January through December), fallow period (January through March and August through December), and growing season (April through July) rainfall, drought index (DI), and soil water condition for 2016, 2017, and the 2001–2017 average are shown in Table 2. Daily maximum air temperature can reach 38 °C in July, while minimum air temperature can drop to –22 °C in January. Average annual temperature 6.4 °C. Long–term climatic records show that annual cumulative air temperature >10 °C is 2240 °C and annual radiation is 5930 MJ/m^2, with 2480 h of sunshine per year. Average annual evaporation is 1531 mm (coefficient of variation: 24.3%), which is three- to four-fold greater than precipitation.

Table 1. Soil physical and water characteristics in 2001.

Soil Layer (cm)	Bulk Density (g cm^{-3})	Upper Limit of Soil Drainage (cm^3 cm^{-3})	Lower Limit of Effective Moisture in Wheat (cm^3 cm^{-3})
0–5	1.29	0.27	0.09
5–10	1.23	0.27	0.09
10–30	1.32	0.27	0.09
30–50	1.20	0.27	0.09
50–80	1.14	0.26	0.09
80–110	1.14	0.27	0.11
110–140	1.13	0.26	0.11
140–170	1.12	0.26	0.12
170–200	1.11	0.26	0.13

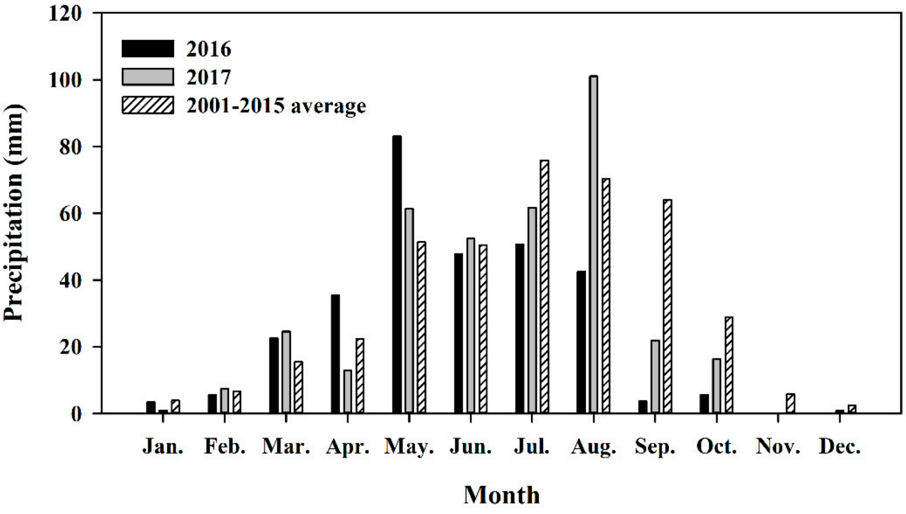

Figure 1. Monthly total precipitation for 2016, 2017, and the 2001-2015 average at the study area.

Table 2. Annual, fallow period, and growing season rainfall, drought index (DI), and soil water condition for 2016, 2017, and the 2001−2015 average [a].

Year	Annual Rainfall (mm)	DI for Annual Rainfall	Annual Soil Water Condition [b]	Fallow Period Rainfall	DI for Fallow Period Rainfall	Fallow Period Soil Water Condition	Growing Season Rainfall (mm)	DI for Growing Season Rainfall	Growing Season Soil Water Condition
2016	300.2	−1.29	Dry	60.8	−2.25	Dry	239.4	0.85	Wet
2017	361.4	−0.47	Dry	175.4	−0.35	Normal	186.0	−0.31	Normal
Average (2001–2015)	396.7	–	–	196.5	–	–	200.2	–	–

[a] Annual (January through December), fallow period (January through March and August through December), and growing season (April through July); [b] Classified as dry, normal, and wet for different time periods for $DI < -0.35$, $-0.35 \le DI \le 0.35$, and $DI > 0.35$, respectively.

2.2. Experimental Design and Agronomic Management

The experimental design was a randomized complete block with four replications.

Plots were 4 m wide × 17 m long in block 1, 21 m long in blocks 2 and 3, and 20 m long in block 4. The long-term experiment included six tillage practice treatments in a two-year spring wheat/pea (*Pisum sativum* L.) rotation, with both phases of the rotation present in each year. All measurements in this study were made from plots planted with wheat. The conventional tillage with no straw

(T) treatment included the removal of all aboveground crop residues at the time of grain harvest before moldboard plowing to a depth of 20 cm. The conventional tillage with straw incorporated (TS) treatment was the same as T, except that all residues from the previous crops were retained and incorporated into the soil with tillage. The no-till with no straw (NT) treatment had all aboveground crop residues removed at the time of grain harvest and no tillage operations. The no-till with straw cover (NTS) treatment was the same as NT, except that all residues from the previous crops were retained. The conventional tillage with plastic mulch (TP) treatment was the same as T, except that alternating ridges (10 cm high × 40 cm wide) and furrows (10 cm wide) were made after harrowing with a ridging implement and all ridges and furrows were covered with colorless plastic film mulch using a plastic mulch laying machine prior to sowing crops in the furrows. The no-till with plastic mulch (NTP) treatment was the same as NT, except that the entire plot area was covered with colorless plastic film mulch using a plastic mulch laying machine. There were the same ridges and furrows with TP.

The spring wheat and pea cultivars were Dingxi 40 and Lvnong 2, respectively. Wheat was sown at a rate of 187.5 kg ha^{-1} in rows spaced 20 cm apart and pea was seeded at 180 kg ha^{-1} in rows spaced 24 cm apart. Immediately prior to the time of plastic mulch laying in the treatments with plastic mulch, all treatments were fertilized with calcium superphosphate (105 kg P_2O_5 ha^{-1} for wheat and pea) and urea (105 and 20 kg N ha^{-1} for wheat and pea, respectively) that was broadcast uniformly over the entire plot area. Wheat was sown on 27 March 2016 and 26 March 2017, and harvested on 25 July 2016 and 20 July 2017. Weeds were removed by hand during the growing season and controlled with herbicides during the fallow period.

2.3. Measurements and Calculation

2.3.1. Precipitation and Drought Index

Daily precipitation was measured with a rainfall canister at the experimental site and DI was calculated as follows [34]:

$$\mathrm{DI} = \frac{Ar - M}{\delta} \tag{1}$$

where Ar is annual rainfall, M is average annual rainfall, and δ is the standard deviation for annual rainfall. Drought index can be used to distinguish among wet (DI > 0.35), normal ($-0.35 \leq \mathrm{DI} \leq 0.35$), and dry (DI < −0.35) soil water conditions for various time periods including on an annual basis, for a growing season, and for a fallow period [34]. Therefore, rainfall during the growing season and fallow period were used to also calculate the DI for these periods in the two study years.

2.3.2. Water Potential and Soil–Leaf Resistance

Water potential indexes were measured at four growth stages of wheat including the seedling stage (30 April 2016 and 12 May 2017), tillering stage (20 May 2016 and 27 May 2017), jointing stage (30 May 2016 and 10 June 2017), and flowering stage (15 June 2016 and 27 June 2017). Three representative plants were randomly selected per plot, their leaves were removed with scissors, and placed into the leaf sample box. Next, a root and soil sample for the selected plants was taken using a soil corer (9-cm inner diameter) from the 0–10 cm soil depths at the seedling stage; at the 0–10 and 10–30 cm soil depths at tillering and jointing; and 0–10, 10–30, and 30–50 cm soil depth at flowering, respectively. Sampled root systems were gently shaken to let the rhizosphere soil fall into the soil sample box, then the root system was placed into the root sample box. Leaf water potential, root water potential, and soil water potential were measured immediately after each were sampled using a dew point water potential meter (WP4C Dewpoint PotentiaMeter, METER Group, Pullman, WA, USA) [35,36].

Transpiration rate and net photosynthetic rate was measured at 9:00 to 11:00 on the morning of the flowering stage (15 June 2016 and 27 June 2017) of wheat with a portable photosynthesis system (model GFS3000, Heinz Walz GmbH, Effeltrich, Germany). Three wheat plants were randomly selected in each plot, the flag leaves of each plant were measured, and the average value of the three plants was obtained as the transpiration rate and net photosynthetic rate of the plot. Soil–leaf water transfer resistance (R_{sl}) was calculated using following equation [37]:

$$R_{sl} = \frac{\Psi_s - \Psi_l}{CT} \quad (2)$$

where R_{sl} is the soil–leaf water transfer resistance; Ψ_s is soil water potential; Ψ_l is leaf water potential; and CT is also transpiration rate.

2.3.3. Soil Water Content, Evapotranspiration, and Evaporation

Soil water content was measured to a depth of 2 m before sowing and after harvest in 2016 and 2017 using the oven-dry method [38] for the 0–5 and 5–10 cm soil depths, and using a time domain reflectometry soil moisture sensor (TRIME-PICO IPH/T3, IMKO GmbH, Ettlingen, BW, Germany) for the 10–30, 30–50, 50–80, 80–110, 110–140, 140–170, and 170–200 cm soil depths. The volumetric moisture content for the 0–5 and 5–10 cm soil depths was calculated by weight moisture content multiplied by corresponding soil bulk density. Evapotranspiration (ET) was calculated using the following equation [9]:

$$ET = P + W_1 - W_2 \quad (3)$$

where ET is evapotranspiration during the growing season; P is precipitation during the growing season; and W_1 and W_2 are water storage in the 0–200 m soil layer before sowing and after harvest, respectively.

Soil evaporation was measured with a micro-evaporator made from polyvinylchloride tubing with the length of 150 mm, internal diameter of 110 mm, and external diameter of 115 mm [39]. On the sampling day, the soil mass of the micro-evaporator was weighed using an electronic balance with a sensitivity of 0.01 g, returned back to its original location in the field, and measured again at 07:00 h the following day. The loss in mass was the amount of evaporation the day before (equivalent to 0.1051 mm g^{-1}). Soil inside the micro-evaporator was changed every three days and after precipitation, the tube emptied of soil, and placed in a new location in the field, which ensured that soil moisture inside the micro-evaporator was consistent with the surrounding soil. The calculation of evaporation in a growth period is based on the daily average evaporation measured during the growth stage multiplied by the number of days during the growth period without precipitation. The amount of transpiration during a growing season is the sum of that for all growth periods in the growing season using the following equation [40]:

$$T = ET - E \quad (4)$$

where T is transpiration during growing season; ET is evapotranspiration during growing season; and E is soil evaporation during growing season.

2.3.4. Yield and Water Use Efficiency

The whole plot was harvested manually using sickles at 5 cm above ground. The edges (0.5 m) of the plot were trimmed and discarded. Biological yield (BY) was measured by natural drying and before threshing. The grain moisture content after threshing was measured by the PM-8188 grain moisture meter (Kett Electric Lab., Tokyo, Japan), repeated five times, and the mean was taken. In addition, grain yield (GY) at 13% water content was calculated. All straw and chaff from stubble incorporated treatments were returned to the original plots immediately after threshing. Water use efficiency was calculated using following equations [9]:

$$WUE_g = \frac{GY}{ET} \quad (5)$$

$$WUE_b = \frac{BY}{ET} \quad (6)$$

where WUE_g and WUE_b are water use efficiency of the grain and biomass yield, respectively.

2.4. Statistical Analysis

All data were checked for normality of distribution using the SPSS 19.0 software (IBM Corp., Chicago, IL, USA) and the Shapiro–Wilk test, and for homoscedasticity using the Levene's test with the general linear model. Data were transformed using either square root or natural log transformation to achieve normality when assumptions could not be met. All data were normal after testing. Analysis of variance was conducted for all dependent variables. Year and tillage practice were considered as fixed effects, and replication was considered a random effect. Differences among means were determined using Tukey's honestly significant different test ($p \leq 0.05$). The linear relationship of water potential indexes with transpiration, BY, GY, WUE_g, and WUE_b were assessed using Pearson's correlation coefficient.

3. Results

3.1. Effect of Tillage Practices on Water Potential at Different Growth Stages

Soil water potential varied with year, tillage practice, soil depth, and growth stage of wheat (Table 3). In 2016, soil water potential with NTS and TP were significantly greater in the 0–10 cm soil layer at the seedling and jointing stages compared to T. In 2017, soil water potential with the different treatments had a similar pattern to that in 2016. On average, compared with T, soil water potential with NTS was significantly greater in the 0–10 cm soil depth at the seedling and jointing stages. Soil water potential with TP was significantly greater than that with T in the 0–10 cm soil depth at the seedling stage and in the 0–10 and 10–30 cm soil depths at the jointing stage. Compared to T, soil water potential with NTP was significantly increased in the 0–10 cm soil depth at the seedling stage, in the 10–30 cm soil depth at tillering stage, and in the 10–30 cm soil depth at the jointing stage.

Table 3. Soil water potential (Mpa) as affected by tillage practice for different growth stages of wheat and soil depths (cm) in 2016 and 2017.

Year	Tillage Practice [b]	Seedling	Tillering		Jointing		Flowering		
		0–10	**0–10**	**10–30**	**0–10**	**10–30**	**0–10**	**10–30**	**30–50**
2016	T	−2.60b [a]	−3.50a	−2.54a	−0.76b	−0.43ab	−2.95a	−2.25a	−2.17a
	NTS	−1.50a	−3.30a	−2.53a	−0.42a	−0.25ab	−2.84a	−2.87a	−3.16a
	NT	−3.03b	−3.00a	−2.66a	−0.53ab	−0.20a	−3.20a	−3.08a	−3.32a
	TS	−2.61b	−3.36a	−3.08a	−0.73b	−0.82b	−2.32a	−2.20a	−3.54a
	TP	−1.52a	−2.20a	−1.65a	−0.38a	−0.62ab	−1.89a	−2.11a	−3.16a
	NTP	−1.15a	−1.92a	−0.94a	−0.51ab	−0.25ab	−2.23a	−2.78a	−2.66a
2017	T	−1.39b	−1.91a	−2.12a	−0.76a	−1.61b	−5.54ab	−4.84b	−5.11c
	NTS	−0.81a	−1.58a	−1.59a	−0.41a	−1.32b	−5.42ab	−4.17b	−3.57b
	NT	−1.26b	−1.96a	−2.05a	−0.63a	−1.48b	−6.50b	−3.82ab	−3.25b
	TS	−0.74a	−1.81a	−1.75a	−0.61a	−1.44b	−5.91b	−4.54b	−2.95ab
	TP	−0.63a	−1.57a	−1.54a	−0.42a	−0.46a	−3.65a	−2.38a	−1.89a
	NTP	−0.60a	−1.33a	−1.37a	−0.63a	−0.81ab	−3.86a	−3.30ab	−3.36b
Average	T	−2.00bc	−2.71a	−2.33b	−0.76b	−1.02bc	−4.24ab	−3.54a	−3.64a
	NTS	−1.16a	−2.44a	−2.06b	−0.41a	−0.79ab	−4.13ab	−3.52a	−3.37a
	NT	−2.15c	−2.48a	−2.40b	−0.58ab	−0.84abc	−4.85b	−3.45a	−3.29a
	TS	−1.68b	−2.59a	−2.42b	−0.67b	−1.13c	−4.11ab	−3.37a	−3.25a
	TP	−1.07a	−1.89a	−1.60ab	−0.40a	−0.54a	−2.77a	−2.25a	−2.53a
	NTP	−0.87a	−1.63a	−1.16a	−0.57ab	−0.53a	−3.04a	−3.04a	−3.01a

[a] Within a column for a given year, means followed by different letters are significantly different ($p \leq 0.05$); [b] T, conventional tillage with no straw; NTS, no-till with straw cover; NT, no-till with no straw; TS, conventional tillage with straw incorporated; TP, conventional tillage with plastic mulch; NTP, no-till with plastic mulch.

Year, tillage practice, soil depth, and growth stage of wheat influenced root water potential (Table 4). In general, compared to T, root water potential was significantly increased with NTS and NT in the 0–10 cm soil depth at the seedling and jointing stages, and with NTS in the 30–50 cm soil depth at flowering. Root water potential was not significantly different between TS and T in all soil layers at every growth stage. Root water potential with TP was significantly greater than that with T in the 0–10 cm soil depth at the seedling, tillering, and jointing stages, and in the 0–10 and 30–50 cm soil depths at flowering. Root water potential with NTP was significantly greater than that with T in the 0–10 cm soil depth at the seedling stage, in the 0–10 and 10–30 cm soil depths at tillering and jointing, and in the 0–10 and 30–50 cm soil depths at flowering.

Table 4. Root water potential (Mpa) as affected by tillage practice for different growth stages of wheat and soil depths (cm) in 2016 and 2017.

Year	Tillage Practice [b]	Seedling	Tillering		Jointing		Flowering		
		0–10	0–10	10–30	0–10	10–30	0–10	10–30	30–50
2016	T	−3.06b[a]	−5.54b	−4.30a	−1.45bc	−1.04a	−3.34a	−4.69a	−5.65a
	NTS	−1.94a	−4.52ab	−3.74a	−0.63ab	−1.71a	−3.92a	−4.55a	−6.01a
	NT	−3.21b	−3.04a	−3.50a	−0.73ab	−0.85a	−3.24a	−4.70a	−6.20a
	TS	−3.03b	−4.44ab	−3.65a	−2.01c	−1.17a	−2.98a	−4.23a	−5.27a
	TP	−1.74a	−3.70ab	−3.60a	−0.41a	−1.79a	−2.37a	−4.25a	−4.29a
	NTP	−1.55a	−2.48a	−2.65a	−0.56a	−1.22a	−2.95a	−4.87a	−5.63a
2017	T	−1.55b	−2.25ab	−2.72b	−2.95d	−2.71c	−8.44c	−7.20c	−10.77c
	NTS	−1.13ab	−2.14ab	−2.50ab	−1.24ab	−1.79abc	−5.82ab	−4.84a	−4.58a
	NT	−1.43b	−2.55b	−2.70b	−1.83bc	−2.16c	−7.02bc	−6.82bc	−8.05b
	TS	−1.26b	−1.94ab	−1.79a	−2.31cd	−1.96bc	−6.06ab	−6.74bc	−7.88b
	TP	−1.24ab	−2.07ab	−2.40ab	−0.66a	−0.87a	−4.24a	−6.54bc	−5.54a
	NTP	−0.73a	−1.65a	−2.01ab	−1.60b	−0.94ab	−4.35a	−5.75ab	−4.42a
Average	T	−2.31c	−3.90c	−3.51b	−2.20c	−1.87b	−5.89b	−5.95a	−8.21b
	NTS	−1.53b	−3.33bc	−3.12ab	−0.94b	−1.75ab	−4.87ab	−4.70a	−5.30a
	NT	−2.32c	−2.80ab	−3.10ab	−1.28b	−1.51ab	−5.13ab	−5.76a	−7.13b
	TS	−2.15c	−3.19bc	−2.72ab	−2.16c	−1.57ab	−4.52ab	−5.49a	−6.58ab
	TP	−1.49ab	−2.89ab	−3.00ab	−0.54a	−1.33ab	−3.30a	−5.40a	−4.92a
	NTP	−1.14b	−2.06a	−2.33a	−1.08b	−1.08a	−3.65a	−5.31a	−5.03a

[a] Within a column for a given year, means followed by different letters are significantly different ($p \leq 0.05$); [b] T, conventional tillage with no straw; NTS, no-till with straw cover; NT, no-till with no straw; TS, conventional tillage with straw incorporated; TP, conventional tillage with plastic mulch; NTP, no-till with plastic mulch.

Leaf water potential differed with year, tillage practice, soil depth, and growth stage of wheat (Table 5). In 2016, compared to T, leaf water potential with NTS was significantly increased at the seedling stage, and not significantly different with NT and TS at any growth stage. Leaf water potential in 2016 was significantly greater with NTP and TP at the seedling stage, and with TP at flowering, compared to T. In 2017, compared to T, leaf water potential with NTS was significantly increased at the seedling and tillering stages; however, leaf water potential with NT was not significantly increased at any growth stage. Leaf water potential was significantly greater with TS than T at the seedling and tillering stages, and with TP than T increased at the seedling, tillering, and jointing stages. On average, leaf water potential with NTS and NTP was significantly greater than that with T at the seedling, tillering, and jointing stages. Leaf water potential with NT and TP was not significantly different when compared to that with T at any growth stage. However, leaf water potential with TS was significantly greater than that with T at the seedling stage.

Table 5. Leaf water potential (Mpa) as affected by tillage practice for different growth stages of wheat in 2016 and 2017.

Year	Tillage Practice [b]	Seedling	Tillering	Jointing	Flowering
2016	T	−7.19c [a]	−7.08abc	−5.27a	−9.41b
	NTS	−4.49ab	−5.73ab	−3.41a	−8.20ab
	NT	−6.77bc	−7.99c	−4.32a	−9.63b
	TS	−5.48abc	−7.39bc	−4.01a	−8.60b
	TP	−4.39a	−5.49ab	−3.48a	−5.87a
	NTP	−3.84a	−4.99a	−3.23a	−7.03ab
2017	T	−5.22c	−3.53b	−3.13b	−9.36b
	NTS	−3.30b	−2.64a	−2.64ab	−8.69ab
	NT	−5.03c	−3.05ab	−3.19b	−8.64ab
	TS	−4.04b	−2.67a	−2.77ab	−9.33ab
	TP	−2.11a	−2.56a	−2.23a	−7.99a
	NTP	−3.35b	−2.47a	−2.16a	−8.74ab
Average	T	−6.21c	−5.31b	−4.20c	−9.39b
	NTS	−3.90ab	−4.19a	−3.02ab	−8.44ab
	NT	−5.90c	−5.52b	−3.75bc	−9.14b
	TS	−4.77b	−5.03b	−3.39abc	−8.96b
	TP	−3.25a	−4.02a	−2.86ab	−6.93a
	NTP	−3.59a	−3.73a	−2.70a	−7.89ab

[a] Within a column for a given year, means followed by different letters are significantly different ($p \leq 0.05$); [b] T, conventional tillage with no straw; NTS, no-till with straw cover; NT, no-till with no straw; TS, conventional tillage with straw incorporated; TP, conventional tillage with plastic mulch; NTP, no-till with plastic mulch.

3.2. Effect of Tillage Practices on Water Potential Gradient at Different Growth Stages

The soil–root water potential gradient was affected by year, tillage practice, soil layer, and growth stage of wheat (Table 6). In 2016, the soil–root water potential gradient was not significantly different among tillage practices at all soil layers at all growth stages. In 2017, the soil–root water potential gradient was significantly reduced with NTS and NTP compared to the other tillage practices in the 0–10 cm soil depth at the jointing stage and in the 0–10 and 30–50 cm soil depths at the flowering stage.

The root–leaf water potential gradient varied with year, tillage practice, soil depth, and growth stage of wheat (Table 7). On average, compared to T, the root–leaf water potential gradient with NTS was significantly reduced at the 0–10 cm soil depth at the seedling stage, 10–30 cm soil depth at jointing stage, and 30–50 cm soil depth at the flowering stage; however, the root–leaf water potential gradient with NT was significantly increased at the 0–10 cm soil depth at the tillering stage. The root–leaf water potential gradient was significantly decreased with TS at the 0–10 cm soil depth at the seedling stage, and with TP at the 0–10 cm soil depth at the seedling stage and 30–50 cm soil depth at flowering, compared to T. The root–leaf water potential gradient with NTP was significantly reduced at the 0–10 cm soil depth at the seedling stage and 30–50 cm soil depth at flowering, compared to T.

The soil–leaf water potential gradient varied with year, tillage practice, soil layer, and growth stage of wheat (Table 8). On average, the soil–leaf water potential gradient with NTS was significantly less than that with T at the 0–10 cm soil depth at the seedling stage and 30–50 cm soil depth at flowering. The soil–leaf water potential gradient with NT and TS was not significantly different from that with T at all soil depths and growth stages. Compared to T, the soil–leaf water potential gradient was significantly decreased with TP at the 0–10 cm soil depth at the seedling stage and at the 30–50 cm soil depth at flowering, and with NTP at the 0–10 cm soil depth at the seedling and jointing stages and at the 30–50 cm soil depth at flowering.

Table 6. Soil-root water potential gradient (Mpa) as affected by tillage practice for different growth stages of wheat and soil depths (cm) in 2016 and 2017.

Year	Tillage Practice [b]	Seedling	Tillering		Jointing		Flowering		
		0–10	0–10	10–30	0–10	10–30	0–10	10–30	30–50
2016	T	0.46a [a]	2.04a	1.77a	0.70ab	0.61a	0.39ab	2.45a	3.47a
	NTS	0.43a	1.22a	1.21a	0.21b	1.46a	1.08a	1.68a	2.84a
	NT	0.18a	0.05a	0.84a	0.20b	0.66a	0.04b	1.63a	2.87a
	TS	0.42a	1.08a	0.57a	1.28a	0.35a	0.66ab	2.03a	1.73a
	TP	0.22a	1.50a	1.95a	0.03b	1.17a	0.48ab	2.13a	1.13a
	NTP	0.41a	0.55a	1.71a	0.06b	0.97a	0.73ab	2.09a	2.97a
2017	T	0.15c	0.33a	0.60a	2.19a	1.09a	2.91a	2.36ab	5.67a
	NTS	0.32bc	0.56a	0.90a	0.83cd	0.46a	0.40b	0.67b	1.01b
	NT	0.16c	0.59a	0.65a	1.20bc	0.68a	0.52b	3.00ab	4.81a
	TS	0.53ab	0.13a	0.04a	1.70ab	0.52a	0.15b	2.20ab	4.93a
	TP	0.61a	0.50a	0.86a	0.24d	0.41a	0.59b	4.16a	3.65a
	NTP	0.13c	0.32a	0.64a	0.97bcd	0.13a	0.50b	2.45ab	1.06b
Average	T	0.31ab	1.19a	1.18a	1.44a	0.85a	1.65a	2.41a	4.57a
	NTS	0.38ab	0.89a	1.06a	0.52ab	0.96a	0.74b	1.17a	1.93c
	NT	0.17b	0.32a	0.75ab	0.70b	0.67a	0.28b	2.32a	3.84ab
	TS	0.47a	0.61a	0.31b	1.49a	0.44a	0.41b	2.11a	3.33abc
	TP	0.42ab	1.00a	1.40a	0.14c	0.79a	0.53b	3.15a	2.39bc
	NTP	0.27ab	0.44a	1.17a	0.52bc	0.55a	0.61b	2.27a	2.01c

[a] Within a column for a given year, means followed by different letters are significantly different ($p \leq 0.05$); [b] T, conventional tillage with no straw; NTS, no-till with straw cover; NT, no-till with no straw; TS, conventional tillage with straw incorporated; TP, conventional tillage with plastic mulch; NTP, no-till with plastic mulch.

Table 7. Root-leaf water potential gradient (Mpa) as affected by tillage practice for different growth stages of wheat and soil depths (cm) in 2016 and 2017.

Year	Tillage Practice [b]	Seedling	Tillering		Jointing		Flowering		
		0–10	0–10	10–30	0–10	10–30	0–10	10–30	30–50
2016	T	4.13a [a]	1.54b	2.78a	3.82a	4.23a	6.07a	4.71a	3.76a
	NTS	2.56a	1.21b	1.99a	2.78a	1.70b	4.27a	3.64a	2.19a
	NT	3.56a	4.94a	4.49a	3.58a	3.46ab	6.39a	4.93a	3.43a
	TS	2.45a	2.95ab	3.74a	2.00a	2.84ab	5.62a	4.37a	3.33a
	TP	2.66a	1.78b	1.88a	3.07a	1.69b	3.50a	1.62a	1.57a
	NTP	2.28a	2.51ab	2.34a	2.67a	2.01b	4.07a	2.16a	1.40a
2017	T	3.67a	1.29a	0.81ab	0.18b	0.42b	0.92d	2.16ab	1.54c
	NTS	2.17b	0.50a	0.14c	1.40a	0.85ab	2.87bc	3.85a	3.36ab
	NT	3.60a	0.50a	0.35abc	1.36a	1.03ab	1.63cd	1.82ab	1.72c
	TS	2.78ab	0.72a	0.87a	0.47b	0.81ab	3.27ab	2.58ab	2.93ab
	TP	0.87c	0.49a	0.16bc	1.57a	1.36a	3.76ab	1.45b	2.60bc
	NTP	2.62ab	0.82a	0.46abc	0.56b	1.23ab	4.39a	2.99ab	3.69a
Average	T	3.90a	1.41b	1.80ab	2.00ab	2.33a	3.49a	3.44a	4.71a
	NTS	2.36bc	0.85b	1.07b	2.09ab	1.28b	3.57a	3.75a	1.60c
	NT	3.58ab	2.72a	2.42a	2.47a	2.25a	4.01a	3.37a	4.12ab
	TS	2.61bc	1.84ab	2.31a	1.23b	1.82ab	4.44a	3.48a	4.13ab
	TP	1.77c	1.14b	1.02b	2.32a	1.53ab	3.63a	1.54a	2.61bc
	NTP	2.45bc	1.67ab	1.40ab	1.61ab	1.62ab	4.23a	2.58a	1.23c

[a] Within a column for a given year, means followed by different letters are significantly different ($p \leq 0.05$); [b] T, conventional tillage with no straw; NTS, no-till with straw cover; NT, no-till with no straw; TS, conventional tillage with straw incorporated; TP, conventional tillage with plastic mulch; NTP, no-till with plastic mulch.

Table 8. Soil-leaf water potential gradient (Mpa) as affected by tillage practice for different growth stages of wheat and soil depths (cm) in 2016 and 2017.

Year	Tillage Practice [b]	Seedling	Tillering		Jointing		Flowering		
		0–10	0–10	10–30	0–10	10–30	0–10	10–30	30–50
2016	T	4.59a [a]	3.58a	4.55a	4.52a	4.84a	6.46a	7.16a	7.23a
	NTS	2.99a	2.43a	3.20a	2.99a	3.15a	5.36a	5.32ab	5.03ab
	NT	3.74a	4.99a	5.33a	3.79a	4.12a	6.43a	6.55ab	6.31ab
	TS	2.87a	4.04a	4.31a	3.28a	3.18a	6.28a	6.40ab	5.06ab
	TP	2.88a	3.28a	3.83a	3.10a	2.86a	3.98a	3.75b	2.70b
	NTP	2.69a	3.06a	4.05a	2.72a	2.98a	4.80a	4.25b	4.36ab
2017	T	3.83a	1.62a	1.41a	2.37a	1.52a	3.83ab	4.52a	11.33a
	NTS	2.48bc	1.05a	1.04a	2.23a	1.32a	3.27bc	4.52a	2.02b
	NT	3.76a	1.09a	1.00a	2.56a	1.70a	2.14c	4.82a	9.61a
	TS	3.31ab	0.85a	0.92a	2.16a	1.33a	3.42bc	4.78a	9.86a
	TP	1.48c	0.99a	1.01a	1.81a	1.77a	4.34ab	5.61a	7.30a
	NTP	2.75ab	1.14a	1.10a	1.53a	1.36a	4.89a	5.44a	2.11b
Average	T	4.21a	2.60a	2.98a	3.44a	3.18a	5.14a	5.84a	9.28a
	NTS	2.74bc	1.74a	2.12a	2.61ab	2.24a	4.31a	4.92a	3.53c
	NT	3.75ab	3.04a	3.16a	3.17ab	2.91a	4.29a	5.69a	7.96a
	TS	3.09abc	2.45a	2.62a	2.72ab	2.26a	4.85a	5.59a	7.46ab
	TP	2.18c	2.14a	2.42a	2.45ab	2.32a	4.16a	4.68a	5.00bc
	NTP	2.72bc	2.10a	2.57a	2.13b	2.17a	4.84a	4.85a	3.24c

[a] Within a column for a given year, means followed by different letters are significantly different ($p \leq 0.05$); [b] T, conventional tillage with no straw; NTS, no-till with straw cover; NT, no-till with no straw; TS, conventional tillage with straw incorporated; TP, conventional tillage with plastic mulch; NTP, no-till with plastic mulch.

3.3. Effects of Tillage Practices on Transpiration Rate and Soil–Leaf Water Transfer Resistance at Flowering

Transpiration rate of wheat at flowering varied with tillage practice (Figure 2). Compared with T, transpiration rate was significantly increased with NTS, TP, and NTP, but not significantly different with NT and TS in all years (Figure 2A,B); on average, NTS, TP, and NTP significantly increased transpiration rate by 103, 143, and 91%, respectively, compared with T. Net photosynthetic rate and soil–leaf water transfer resistance at flowering were impacted by tillage practices (Figures 2 and 3). Net photosynthetic rate was significantly increased with NTS, TP, and NTP, but was not significantly different with NT and TS (Figure 2C,D); over the two years, NTS, TP, and NTP significantly increased the net photosynthetic rate by 20, 19, and 19%, respectively, when compared to T. Compared to T, soil–leaf water transfer resistance at all soil layers was significantly reduced with NTS, TP, and NTP, but not significantly different with NT and TS (Figure 3). Averaged across years and soil layers, compared to T, the soil–leaf water transfer resistance with NTS, TP, and NTP was significantly decreased by 66, 70, and 63%, respectively.

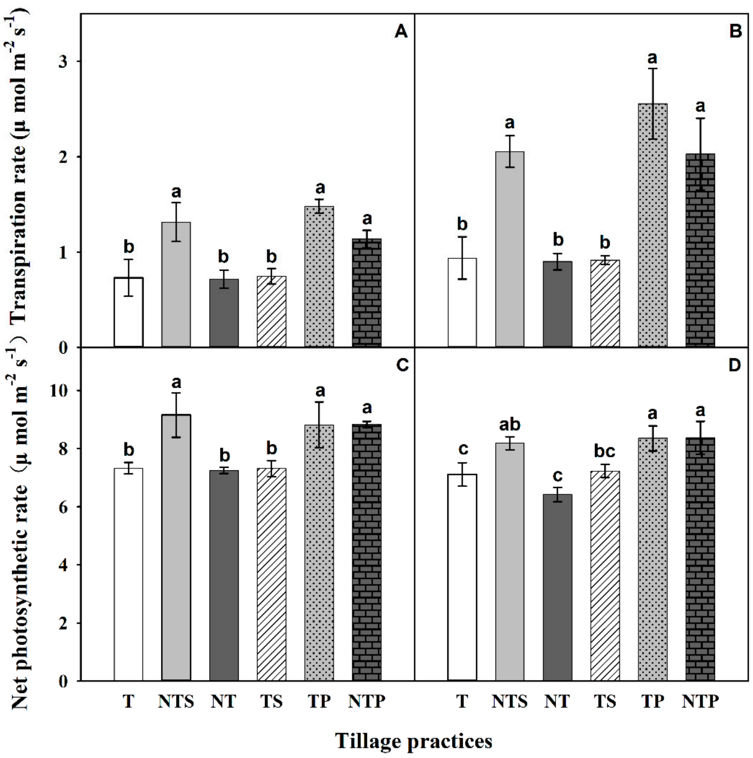

Figure 2. Transpiration rate at the flowering stage of wheat in 2016 (**A**) and 2017 (**B**) and net photosynthetic rate at the flowering stage of wheat in 2016 (**C**) and 2017 (**D**) as affected by tillage practice. T, conventional tillage with no straw; NTS, no-till with straw cover; NT, no-till with no straw; TS, conventional tillage with straw incorporated; TP, conventional tillage with plastic mulch; NTP, no-till with plastic mulch. Bars with different letters indicate treatment means that are significantly different ($p \leq 0.05$). Error bars denote standard errors of the means ($n = 4$).

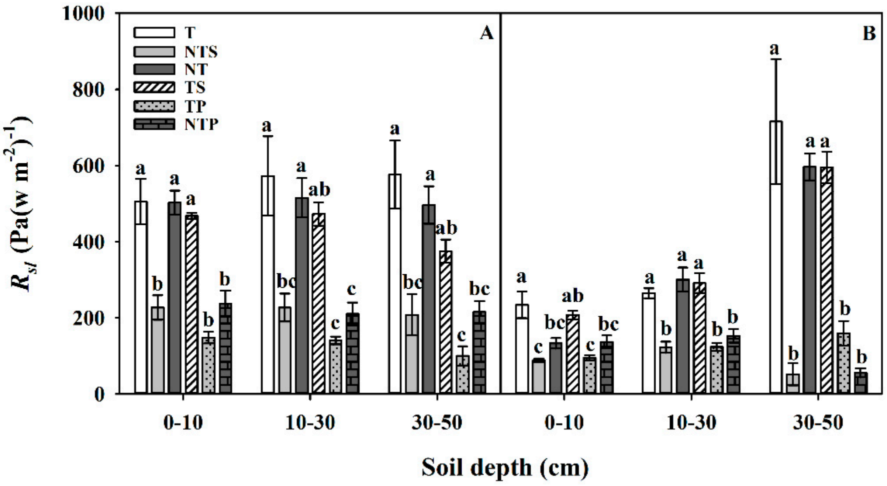

Figure 3. Soil-leaf water transfer resistance (Rsl) at the flowering stage of wheat in 2016 (**A**) and 2017 (**B**) as affected by tillage practice for different soil layers. T, conventional tillage with no straw; NTS, no-till with straw cover; NT, no-till with no straw; TS, conventional tillage with straw incorporated; TP, conventional tillage with plastic mulch; NTP, no-till with plastic mulch. Within a year for a given soil layer, bars with different letters indicate treatment means that are significantly different ($p \leq 0.05$). Error bars denote standard errors of the means ($n = 4$).

3.4. Effect of Tillage Practices on Yield and Water Use Efficiency

Tillage practice significantly affected transpiration at flowering, BY, WUE$_b$, GY, and WUE$_g$ (Table 9). Over the two years, compared with T, transpiration with NTS, TP, and NTP was significantly increased by 40, 64, and 76%, respectively; however, transpiration was not significantly different with NT and TS. Compared to T, BY was significantly increased with NTS, TP, and NTP by 18, 36, and 40%, respectively; however, it was not significantly different with NT and TS. Water use efficiency of BY was significantly increased with TP and NTP by 25 and 22%, respectively, but was not significantly different with NTS and TS, compared to T. Grain yield with NTS, TP, and NTP was significantly increased by 28, 22 and 24%, respectively, compared to T; however, it was not significantly different among NT, TS, and T. Water use efficiency of GY with NTS, TP and NTP was significantly increased by 24, 26, and 24%, respectively, but not significantly different with NT and TS, compared to T.

Table 9. Transpiration at the growing season, biomass and grain yields, and water use efficiency of grain yield and biomass yield (WUE$_b$ and WUE$_g$, respectively) of wheat as affected by tillage practice in 2016 and 2017.

Year	Tillage Practice [b]	Transpiration (mm)	Biomass Yield (kg ha^{-1})	WUE$_b$ (kg ha^{-1} mm^{-1})	Grain Yield (kg ha^{-1})	WUE$_g$ (kg ha^{-1} mm^{-1})
2016	T	176.4c [a]	4107d	15.38bc	1430c	5.36bc
	NTS	209.1b	4798b	16.73ab	1859a	6.48a
	NT	177.3c	3916d	14.75c	1216d	4.50c
	TS	171.1c	4367c	17.08a	1560bc	6.13ab
	TP	214.5b	4669b	18.08a	1686ab	6.55a
	NTP	252.0a	5150a	17.25a	1839a	6.15ab
2017	T	58.7c	2498bc	13.77b	–	–
	NTS	120.2b	2994b	13.09bc	–	–
	NT	68.6c	2090c	10.70c	–	–
	TS	84.7c	2369bc	11.11bc	–	–
	TP	170.0a	4310a	18.23a	–	–
	NTP	161.4a	4074a	18.29a	–	–
Average	T	117.58c	3303c	14.58b	1460bc	5.48bc
	NTS	164.68b	3896b	14.91b	1862a	6.78a
	NT	122.96c	3003c	12.73c	1416c	5.56c
	TS	127.88c	3368c	14.10bc	1647b	6.28b
	TP	192.26a	4489a	18.16a	1776ab	6.90ab
	NTP	206.70a	4612a	17.77a	1815ab	6.78ab

[a] Within a column for a given year, means followed by different letters are significantly different ($p \leq 0.05$); [b] T, conventional tillage with no straw; NTS, no-till with straw cover; NT, no-till with no straw; TS, conventional tillage with straw incorporated; TP, conventional tillage with plastic mulch; NTP, no-till with plastic mulch.

3.5. Correlations of Water Potential Indexes with Transpiration, Biomass and Grain Yields, and Water Use Efficiency of Grain and Biomass Yields

Significant correlations among the water potential indexes, transpiration at growing season, BY, WUE$_b$, GY, and WUE$_g$ of wheat were observed (Table 10). Soil water potential, root water potential, and leaf water potential at the seedling stage was highly significant and positively associated with transpiration, BY, WUE$_b$, GY, and WUE$_g$. Soil water potential, root water potential, and leaf water potential at other growth stages showed different patterns. The root–leaf water potential gradient and soil–leaf water potential gradient at the seedling stage had a significant negative correlation with transpiration, BY, WUE$_b$, GY, and WUE$_g$. The soil–root water potential gradient, root–leaf water potential gradient, and soil–leaf water potential gradient at the 30–50 cm soil depth at flowering had a significant negative correlation with transpiration, BY, WUE$_b$, GY, and WUE$_g$. The soil–root water potential gradient, root–leaf water potential gradient, and soil–leaf water potential gradient at other growth stages showed different patterns.

Table 10. Pearson's correlation coefficient for correlations of water potential indexes with transpiration, biomass and grain yields, and water use efficiency of biomass and grain yields (WUE_b and WUE_g, respectively) across years for different growth stages of wheat and soil layers.

Growth Stage	Soil Depth (cm)	Water Potential Index [b]	Transpiration	Biomass Yield	WUE_b	Grain Yield	WUE_g
Seeding	0–10	S	0.888** [a]	0.854**	0.757**	0.839**	0.646**
		R	0.892**	0.834**	0.738**	0.767**	0.531*
		L	0.839**	0.861**	0.705**	0.826**	0.732**
		S-R	0.104	0.171	0.158	0.333	0.443
		R-L	−0.639**	−0.699**	−0.543*	−0.689**	−0.689**
		S-L	−0.654**	−0.704**	−0.543*	−0.665**	−0.645**
Tillering	0–10	S	0.615**	0.480*	0.461	0.183	−0.043
		R	0.649**	0.561*	0.376	0.331	0.093
		L	0.875**	0.844**	0.764**	0.783**	0.547*
		S-R	−0.073	−0.128	0.090	−0.203	−0.177
		R-L	−0.282	−0.330	−0.414	−0.471*	−0.450
		S-L	−0.369	−0.463	−0.395	−0.676**	−0.634**
	10–30	S	0.769**	0.686**	0.657**	0.551*	0.327
		R	0.511*	0.357	0.278	0.335	0.092
		S-R	0.37	0.442	0.497*	0.301	0.300
		R-L	−0.505*	−0.588*	−0.566*	−0.543*	−0.485*
		S-L	−0.325	−0.370	−0.299	−0.428	−0.356
Jointing	0–10	S	0.490*	0.510*	0.371	0.442	0.483*
		R	0.687**	0.703**	0.542*	0.428	0.356
		L	0.765**	0.705**	0.461	0.614**	0.342
		S-R	−0.681**	−0.694**	−0.542*	−0.383	−0.285
		R-L	−0.131	−0.049	0.054	−0.234	−0.008
		S-L	−0.660**	−0.595**	−0.380	−0.518*	−0.233
	10–30	S	0.765**	0.735**	0.644**	0.465	0.348
		R	0.551*	0.581*	0.385	0.334	0.121
		S-R	−0.033	−0.085	0.053	−0.019	0.118
		R-L	−0.590**	−0.489*	−0.315	−0.557*	−0.36
		S-L	−0.526*	−0.472*	−0.236	−0.488*	−0.233
Flowering	0–10	S	0.664**	0.664**	0.786**	0.470*	0.407
		R	0.649**	0.607**	0.613**	0.455	0.419
		L	0.722**	0.730**	0.721**	0.530*	0.505*
		S-R	−0.235	−0.146	0.058	−0.156	−0.189
		R-L	−0.021	−0.115	−0.089	−0.057	−0.082
		S-L	−0.243	−0.258	−0.038	−0.205	−0.262
	10–30	S	0.489*	0.503*	0.634**	0.169	0.278
		R	0.289	0.239	0.124	0.248	−0.006
		S-R	0.093	0.147	0.338	−0.096	0.201
		R-L	−0.444	−0.486*	−0.558*	−0.301	−0.455
		S-L	−0.554*	−0.552*	−0.428	−0.566*	−0.440
	30–50	S	0.427	0.328	0.456	0.243	0.399
		R	0.807**	0.748**	0.585*	0.642**	0.471*
		S-R	−0.753**	−0.731**	−0.475*	−0.647**	−0.367
		R-L	−0.775**	−0.771**	−0.559*	−0.781**	−0.528*
		S-L	−0.803**	−0.790**	−0.547*	−0.757**	−0.479*

[a] Correlation coefficients followed by * and ** are significant at $P \leq 0.05$ and 0.01, respectively; [b] S, soil water potential; R, root water potential; L, leaf water potential; S-R, soil-root water potential gradient; R-L, root-leaf water potential gradient; S-L, soil-leaf water potential gradient.

4. Discussion

4.1. Effects of Tillage Practices on Water Potential in the Soil–Plant System

Soil, roots, and leaves are important indicators of whether plants are subject to drought stress [41–43], and have been employed in the selection of appropriate tillage practices. Tillage practices can affect soil, root, and leaf water potential [44,45]. In this study, NTS significantly increased soil water potential in the 0–10 cm soil depth at the seedling and jointing stages of wheat compared to T because NTS increased topsoil moisture at the seedling stage. However, with wheat growth and development, canopy coverage increased, transpiration dominated evapotranspiration, and the positive effect of straw mulching on topsoil moisture gradually weakened [26,46], thus NTS did not significantly increase the soil water potential at flowering. Conventional tillage and no-till improved soil water potential compared to T in the 0–30 cm soil depths at all growth stages, mainly because plastic film mulching reduced soil evaporation, which led to greater soil water moisture throughout the growing season [47]. No-till with straw cover, TP, and NTP increased leaf water potential compared to T at all growth stages, in agreement with results from previous studies [44,48]. However, Zhang et al. [49] found that NTS reduced leaf water potential by 11% compared to T. This discrepancy is likely to be due to differences in soils and early rainfall prior to measurement. The study reported by Zhang et al. (1999) was conducted on a quaternary red clay soil with high viscosity, and long-term no-till led to subsurface soil compaction and shallow root systems. The present study was conducted on a deep loess soil with deep uniform texture and high water storage capacity [50], which is favorable for the growth and development of crop root systems.

Water potential gradients drive water transport from soil to plants, with a greater water potential gradient resulting in faster water absorption [51]. In this study, NTS, TP, and NTP reduced the soil–root water potential gradient in the 30–50 cm soil depth at the flowering of wheat. No-till with straw cover, TP, and NTP significantly decreased the root–leaf water potential gradient compared to T at the 0–10 cm soil depth at the seedling stage and 30–50 cm soil depth at flowering. These treatments also significantly reduced the soil–leaf water potential gradient at the 0–10 cm soil depth at the seedling stage and 30–50 cm soil depth at flowering, most likely because they stored more water from the fallow period. Moreover, wheat canopy coverage reaches a maximum at flowering, thereby limiting evaporation after this stage.

Water transfer resistance exists in the process of water transport from soil to plants [52]. In this study, NTS, TP, and NTP reduced the soil–leaf water transfer resistance at flowering of wheat compared to T. This could be due to NTS, TP, and NTP having increased root length and root surface area, and more favorable spatial distribution of roots for water uptake [53]. This was demonstrated in this study, as NTS, TP, and NTP had greater soil water absorption by plants than T.

In this study, NTS, TP, and NTP significantly increased the transpiration and net photosynthetic rate of wheat at flowering compared to T, as shown in previous studies [54–56]. The net photosynthetic rate of wheat flag leaves has been reported to be 24 to 39% higher with NTS compared to conventional tillage, and also has a significantly higher transpiration rate [54,57]. In contrast, Jiang et al. [58] found that NTS reduced the photosynthetic rate of wheat, likely because their straw cover was applied after sowing, resulting in less soil moisture stored during the fallow season. Straw coverage in this study occurred after harvest, leading to more soil moisture stored during the fallow season, thereby enabling an increase in photosynthetic rate. Transpiration is fundamental to understanding crop water use efficiency [10]. In this study, transpiration with NTS, TP, and NTP was significantly increased compared to T, mainly because NTS, TP, and NTP increased precipitation infiltration and reduced soil evaporation [23,47,59].

Biomass yield of wheat was significantly greater with NTS, TP, and NTP compared to T. Garofalo and Rinaldi [60] found that a greater rate of transpiration was associated with greater BY. However, Dam et al. [61] found that the long-term BY of maize did not differ between NTS and T. This may be attributable to differences in soil texture at the experimental sites, which was sandy loam in their study and loess in the present study. In agreement with our results, Zhang et al. [62] found that plastic mulching increased the BY of maize. This could be due to enhanced crop growth resulting from greater soil temperature [63,64], soil moisture [62], and radiation capture [65] with plastic mulching.

4.2. *Effects of Tillage Practices on Grain Yield and Water Use Efficiency*

Conservation tillage practices have been shown to increase soil water storage, wheat yield, and WUE on the semi-arid Loess Plateau of China [27,66]. However, Pittelkow et al. [15] found that conservation tillage practices did not increase the GY of cereals in moist regions. This is likely to be because the impact of conservation tillage on yield varies among climatic zones. The improvement of wheat GY and WUE_g with NTS, TP, and NTP compared to T in this study can be attributed to increased water potential and decreased water potential gradient and water transfer resistance, thus enhancing transpiration and BY.

5. Conclusions

This study demonstrated that NTS, TP, and NTP significantly increased grain yield and WUE_g as a result of increased water potential, decreased water potential gradient, and water transfer resistance, and led to increases in transpiration rate, transpiration, and biomass yield. These results demonstrate that no-till with straw cover, conventional tillage with plastic mulch, and no-till with plastic mulch are suitable tillage practices for the sustainable intensification of wheat production in semi-arid areas.

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