Peer-reviewed version available at *Agronomy* **2019**, *9*, 583; doi:10.3390/agronomy9100583

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

Zhengkai Peng[a,b], Linlin Wang[a,b], Junhong Xie[a,b], Lingling Li[a,b*], Jeffrey A. Coulter[c], Renzhi Zhang[a,d] , Zhuzhu Luo[a,d], Jana Kholova[e], Sunita Choudhary[e]

[a] Gansu Provincial Key Laboratory of Aridland Crop Science, Gansu Agricultural University, Lanzhou 730070, China

[b] College of Agronomy, Gansu Agricultural University, Lanzhou 730070, China

[c] Department of Agronomy and Plant Genetics, University of Minnesota, St. Paul, MN 55108, USA

[d] College of Resource and Environment, Gansu Agricultural University, Lanzhou 730070, China

[e] International Crops Research Institute for Semi-arid Tropics(ICRISAT), Patancheru 502324, India

[*]Corresponding author at College of Agronomy / Gansu Provincial Key Laboratory of Aridland Crop Science, Gansu Agricultural University, Lanzhou 730070, China.

E-mail address: lill@gsau.edu.cn (L. Li)

Peer-reviewed version available at *Agronomy* **2019**, *9*, 583; doi:10.3390/agronomy9100583

Abstract

Water availability is a major constraint for spring wheat production on the western Loess Plateau of China. The impact of tillage practices on water potential, water potential gradient, water transfer resistance, yield, and water use efficiency (WUE_g) of spring wheat was monitored on the western Loess Plateau in 2016 and 2017. Six tillage practices were assessed, 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 and root water potential at the seedling stage and leaf water potential at the seedling, tillering, jointing, and flowering stages, compared to T. These treatments also significantly reduced the soil-leaf water potential gradient at the 0-10 cm soil layer at the seedling stage and at the 30-50 cm soil layer at flowering, 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 treatments significantly increased biomass yield (BY) by 18, 36, and 40%, respectively, and grain yield (GY) by 28, 22, and 24%, respectively, with corresponding increases in WUEg of 24, 26, and 24%, respectively. These results demonstrate that NTS, TP, and NTP improved GY and WUEg of spring wheat by decreasing the soil-leaf water potential gradient and soil-leaf water transfer resistance and enhancing transpiration, and are suitable tillage practices for

Peer-reviewed version available at *Agronomy* **2019**, *9*, 583; doi:10.3390/agronomy9100583

sustainable intensification of wheat production in semi-arid areas.

Keywords: Conservation tillage; Water potential; Water potential gradient; Water transfer resistance; Water use efficiency

1. Introduction

Wheat (*Triticum aestivum* L.) is a major food crop in China and in the world, which plays an important role in ensuring China's 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 is a major goal for advancing sustainable intensification of crop production on the western Loess Plateau that will have great impact at local and regional scales [9].

Water use efficiency depends on the amount of water absorbed by plants, of which the majority is lost by transpiration [10]. Water absorption depends on the free energy of water in plants, which is shown as the level of water potential in the soil-plant-atmosphere continuum [11]. The lower the water potential of plant, the stronger the water absorption capacity. Kang [12] found that transpiration rate was positively correlated with the water potential difference of the leaf-atmosphere system. Yang et al. [13] found that leaf water

Peer-reviewed version available at *Agronomy* **2019**, *9*, 583; doi:10.3390/agronomy9100583

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 display 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 is a technique that 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, 19], thereby increasing rainfall infiltration and soil water holding capacity [20, 21], reducing soil evaporation and enhancing crop growth, yield, and water use efficiency [22-24]. No-till with straw cover has been shown to improve grain yield by 13%, and water use efficiency 7.6% in winter spring wheat on the Loess Plateau of China [25]. No-till with straw cover has been shown to improve grain yield by 153%, and water use efficiency by 46% in wheat and maize (*Zea mays* L.) relay-planting system on Hexi Corridor of northwestern China with typical temperate arid zone of continent [26]. Subsoil tillage with 50% chopped straw mulching has been shown to improve grain yield by 5-7%, and water use efficiency by 51-52% in maize on the Huang–Huai–Hai valley with mean annual precipitation is 556.2 mm [27]. Ridge mulched with plastic film has been shown to improve grain yield by 30%, and water use efficiency 35% in wheat on the Loess Plateau of

Peer-reviewed version available at Agronomy 2019, 9, 583; doi:10.3390/agronomy9100583

China [4]. However, the mechanism by which conservation tillage improves water use efficiency from the perspective of water potential gradient has not been reported. 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 water use efficiency of spring wheat to provide a theoretical basis for improving water use efficiency and conservation tillage development on the western Loess Plateau.

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 located at the Rainfed Agricultural Experimental station of Gansu Agricultural University (35°28′N, 104°44′E, elevation: 1971 m above sea level) 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 [28], is a Calcaric Cambisol according to the FAO (1990) [29], soil classification, and is primarily used for annual crop production [30]. This soil type has a sandy loam texture with ≥50% sand. Detailed soil physical and water characteristics at the experimental site before sowing in 2001 are presented in Table 1. Annual precipitation at the experimental site was 300.2 mm in 2016, 361.4 mm in 2017,

Peer-reviewed version available at *Agronomy* **2019**, *9*, 583; doi:10.3390/agronomy9100583

and 396.7 mm for the 2001-2015 average, and is shown monthly in Fig. 1. 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 at the experimental site for 2016, 2017, and the 2001-2017 average are shown in Table 2. Daily maximum air temperature at the experimental site can reach 38°C in July, while minimum air temperature can drop to –22°C in January. 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 hours of sunshine per year. Average annual evaporation at the experimental site is 1531 mm (coefficient of variation: 24.3%), which is three- to four-fold greater than precipitation.

2.2. Experimental design and agronomic management

The experimental design was a randomized complete block with four replications. Each plot was 4 m wide × 20 m long. 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 to wheat. The conventional tillage with no straw (T) treatment included 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

Peer-reviewed version available at Agronomy 2019, 9, 583; doi:10.3390/agronomy9100583

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 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 [9]:

$$\mathrm{DI} = \frac{Ar - M}{\delta} \qquad (1)$$

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 ≤ DI ≤ 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 [9]. Therefore, rainfall during the growing season and fallow period were used to also calculate 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 in per plot, their leaves were removed with a 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

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 9 August 2019

Peer-reviewed version available at Agronomy 2019, 9, 583; doi:10.3390/agronomy9100583

layer at the seedling stage, at the 0-10 and 10-30 cm soil layers at tillering and jointing, and 0-10, 10-30, 30-50 cm soil layer at flowering, respectively. Sampled root systems were gently shaken to let 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) [31, 32].

Transpiration rate and net photosynthetic rate was measured at 9:00 to 11:00 on the morning of 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 [12]:

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

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 [33] for the 0-5 and 5-10

Peer-reviewed version available at Agronomy 2019, 9, 583; doi:10.3390/agronomy9100583

cm soil layers, and using a time domain reflectometry soil moisture sensor (TRIME-PICO IPH/T3, IMKO GmbH, Ettlingen, Germany) for the 10-30, 30-50, 50-80, 80-110, 110-140, 140-170, and 170-200 cm soil layers. Evapotranspiration (ET) was calculated using following equation [9]:

$$\mathrm{ET} = \mathrm{P} + \mathrm{W}_1 - \mathrm{W}_2 \qquad (3)$$

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 0-200m 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 [34]. One tube per plot was installed to remove undisturbed soil at 07:00 h, with plastic film used to seal the base of the undisturbed soil. Mass of the soil core was measured using an electronic balance with a sensitivity of 0.01 g. The soil was then placed back in its original location in the field and the soil was measured at 07:00 h on the next day. The loss in mass was the amount of evaporation (equivalent to 0.1051 mm g^{-1}). Soil inside the micro-evaporator was changed every 3 days and after precipitation, tube emptied of soil and placed in a new location in the field, which ensure that soil moisture inside the micro-evaporator is 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

Peer-reviewed version available at *Agronomy* **2019**, *9*, 583; doi:10.3390/agronomy9100583

of transpiration during a growing season is the sum of that for all growth periods in the growing season using following equation [35]:

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

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, repeated 5 times, and the mean was taken. In addition, grain yield (GY) at 13% water content is 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]:

$$\mathrm{WUE}_g = \frac{GY}{ET} \qquad (5)$$

$$\mathrm{WUE}_b = \frac{BY}{ET} \qquad (6)$$

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

2.4. Statistical analysis

Data were analyzed at $P \leq 0.05$ using SPSS 19.0 software (IBM Corp.,

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 9 August 2019

Peer-reviewed version available at Agronomy 2019, 9, 583; doi:10.3390/agronomy9100583

Chicago, USA). Analysis of variance was conducted for all dependent variables. Year and tillage practice were considered fixed effects, and replication was considered a random effect. Differences among means were determined using Tukey's honestly significant different test. 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 layer, 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 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 layer at the seedling and jointing stages. Soil water potential with TP was significantly greater than that with T in the 0-10 cm soil layer at the seedling stage and in the 0-10 and 10-30 cm soil layers at jointing stage. Compared to T, soil water potential with NTP was significantly increased in the 0-10 cm soil layer at the seedling stage, in the 10-30 cm soil layer at tillering stage, and in the 10-30 cm soil layer at jointing stage.

Year, tillage practice, soil layer, 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 layer at the seedling and jointing stages, and with NTS in the 30-50 cm soil layer 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 layer at the seedling, tillering, and jointing stages, and in the 0-10 and 30-50 cm soil layers at flowering. Root water potential with NTP was significantly greater than that with T in the 0-10 cm soil layer at the seedling stage, in the 0-10 and 10-30 cm soil layers at tillering and jointing, and in the 0-10 and 30-50 cm soil layers at flowering.

Leaf water potential differed with year, tillage practice, soil layer, 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 staged. Leaf water potential in 2016 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

Peer-reviewed version available at Agronomy 2019, 9, 583; doi:10.3390/agronomy9100583

stages. Leaf water potential with NT and TP was not significantly different 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.

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 layer at jointing stage and in the 0-10 and 30-50 cm soil layers at flowering stage.

The root-leaf water potential gradient varied with year, tillage practice, soil layer, 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 layer at the seedling stage, 10-30 cm soil layer at jointing stage, and 30-50 cm soil layer at flowering stage; however, the root-leaf water potential gradient with NT was significantly increased at 0-10 cm soil layer at tillering stage. The root-leaf water potential gradient was significantly decreased with TS at the 0-10 cm soil layer at the seedling stage, and with TP at the 0-10 cm soil layer at the seedling stage and 30-50 cm soil layer at flowering, compared to T. The root-

Peer-reviewed version available at Agronomy 2019, 9, 583; doi:10.3390/agronomy9100583

leaf water potential gradient with NTP was significantly reduced at the 0-10 cm soil layer at the seedling stage and 30-50 cm soil layer 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 layer at the seedling stage and 30-50 cm soil layer at flowering. The soil-leaf water potential gradient with NT and TS was not significantly different from that with T at all soil layers and growth stages. Compared to T, the soil-leaf water potential gradient was significantly decreased with TP at the 0-10 cm soil layer at the seedling stage and at the 30-50 cm soil layer at flowering, and with NTP at the 0-10 cm soil layer at the seedling and jointing stages and at the 30-50 cm soil layer at flowering.

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 (Fig. 2). In 2016 and 2017, compared with T, transpiration rate was significantly increased with NTS, TP, and NTP, but not significantly different with NT and TS (Fig. 2A, B). On average, compared with T, NTS, TP, and NTP significantly increased transpiration rate by 103, 143, and 91%, respectively (data not shown).

Net photosynthetic rate of wheat at flowering varied among tillage

Peer-reviewed version available at *Agronomy* **2019**, *9*, 583; doi:10.3390/agronomy9100583

practices (Fig. 2). In 2016 and 2017, compared with T, net photosynthetic rate was significantly increased with NTS, TP, and NTP, but not significantly different with NT and TS (Fig. 2C, D). On average, NTS, TP, and NTP significantly increased net photosynthetic rate by 20, 19, and 19%, respectively, compared to T (data not shown).

Soil-leaf water transfer resistance of wheat at flowering was also affected by tillage practice (Fig. 3). In 2016 and 2017, 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 (Fig. 3A, B). Averaged across years and soil layers, compared to T, soil-leaf water transfer resistance with NTS, TP, and NTP was significantly decreased by 66, 70, and 63%, respectively (data not shown).

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). In 2016, transpiration with NTS, TP, and NTP was significantly increased by 19, 22 and 43%, respectively, compared to T, and BY with NTS, TS, TP, and NTP was significantly increased by 17, 6, 14, and 25%, respectively. Water use efficiency of BY with TS, TP, and NTP was significantly increased by 11, 18, and 12%, respectively, compared to T. Grain yield with NTS, TP, and NTP was significantly increased by 30, 18, and 29%, respectively, compared to T, and WUE_g was significantly increased by 21, 22, and 15%,

Peer-reviewed version available at Agronomy 2019, 9, 583; doi:10.3390/agronomy9100583

respectively. On average, 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.

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 water potential indexes, transpiration at growing season, BY, WUE_b, GY, and WUE_g of wheat were observed (Table10). Soil water potential in the 0-10 cm soil layer at the seedling stage was highly significant and positively associated with transpiration , BY, WUE_b, GY, and WUE_g. Soil water potential in the 0-10 cm soil layer at tillering was positively associated with transpiration (r = 0.615, P < 0.01) and BY (r = 0.480, P < 0.05). Soil water potential in the 10-30 cm soil layer at tillering was significantly

Peer-reviewed version available at Agronomy 2019, 9, 583; doi:10.3390/agronomy9100583

positively associated with transpiration, BY, WUE_b, and GY. Soil water potential in the 0-10 cm soil layer at jointing was significantly positively associated with transpiration and BY. Soil water potential in the 10-30 cm soil layer at jointing was significantly positively associated with transpiration, BY, and WUE_b. Soil water potential in the 0-10 cm soil layer at flowering was positively associated with transpiration, BY, WUE_b, and GY. Soil water potential in the 10-30 cm soil layer at flowering was positively associated with transpiration, BY, and WUE_b.

Root water potential in the 0-10 cm soil layer at the seedling stage of wheat was significantly positively associated with transpiration, BY, WUE_b, GY, and WUE_g (Table 10). Root water potential in the 0-10 cm soil layer at tillering was positively associated with transpiration ($r = 0.649$, $P < 0.01$) and BY ($r = 0.561$, $P < 0.05$). Root water potential in the 10-30 cm soil layer at tillering was positively associated with transpiration ($r = 0.511$, $P < 0.05$). Root water potential in the 0-10 cm soil layer at jointing was significantly positively associated with transpiration, BY, and WUE_b. Root water potential in the 10-30 cm soil layer at jointing was significantly positively associated with transpiration and BY. Root water potential in the 0-10 cm soil layer at flowering exhibited a significant positive associated with transpiration, BY, and WUE_b. Root water potential in the 30-50 cm soil layer at flowering was significantly positively associated with transpiration, BY, WUE_b, GY, and WUE_g.

Leaf water potential at the seedling stage of wheat had a significant positively association with transpiration at flowering, BY, WUE_b, GY, and

Peer-reviewed version available at Agronomy 2019, 9, 583; doi:10.3390/agronomy9100583

WUEg (Table 10). Leaf water potential at tillering was significantly positively associated with transpiration, BY, WUE_b, GY, and WUE_g. Leaf water potential at jointing was significantly and positively associated with transpiration, BY, and GY. Leaf water potential at flowering was positively associated with transpiration, BY, WUE_b, GY, and WUE_g.

The soil-root water potential gradient in the 10-30 cm soil layer at tillering of wheat was significantly positively associated with WUE_b (Table 10). The soil-root water potential gradient in the 0-10 cm soil layer at jointing had a significant negative correlation with transpiration, BY, and WUE_b. The soil-root water potential gradient in the 30-50 cm soil layer at flowering showed a negative correlation with transpiration, BY, WUE_b, and GY.

The root-leaf water potential gradient at the 0-10 cm soil layer at the seedling stage of wheat had a significant negative correlation with transpiration, BY, WUE_b, GY, and WUE_g (Table 10). The root-leaf water potential gradient at the 0-10 cm soil layer at tillering was significantly negatively associated with GY. The root-leaf water potential gradient at the 10-30 cm soil layer at tillering was significantly negatively associated with transpiration, BY, WUE_b, GY, and WUE_g. The root-leaf water potential gradient at the 10-30 cm soil layer at jointing exhibited a significant negatively correlation with transpiration, BY, and GY. The root-leaf water potential gradient at the 10-30 cm soil layer at flowering was significantly negatively associated with BY and WUE_b. The root-leaf water potential gradient at the 30-

Peer-reviewed version available at Agronomy 2019, 9, 583; doi:10.3390/agronomy9100583

50 cm soil layer at flowering had a significant negative correlation with transpiration, BY, WUE_b, GY, and WUE_g.

The soil-leaf water potential gradient at the 0-10 cm soil layer at the seedling stage of wheat showed a significant negatively association with transpiration, BY, WUE_b, GY, and WUE_g. The soil-leaf water potential gradient at the 0-10 cm soil layer at tillering was significantly negatively associated with GY and WUE_g. The soil-leaf water potential gradient at the 0-10 cm soil layer at jointing was had a significant negative correlation with transpiration, BY, and GY. The soil-leaf water potential gradient at the 10-30 cm soil layer at jointing was significantly negatively associated with transpiration, BY, and GY. The soil-leaf water potential gradient at the 10-30 cm soil layer at flowering exhibited a significantly negative associated with transpiration, BY, and GY. The soil-leaf water potential gradient at the 30-50 cm soil layer at flowering was significantly negatively associated with transpiration, BY, WUE_b, GY, and WUE_g.

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 [36-38], and have been employed in the selection of appropriate tillage practices. Tillage practices can affect soil, root, and leaf water potential [39, 40]. In this study, NTS significantly increased soil water potential in the 0-10 cm soil layer at the seedling and jointing stages of wheat

Peer-reviewed version available at Agronomy 2019, 9, 583; doi:10.3390/agronomy9100583

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 [24, 41], thus NTS did not significantly increase soil water potential at flowering. Conventional tillage and no-till improved soil water potential compared to T in the 0-30 cm soil layers at all growth stages, mainly because plastic film mulching reduced soil evaporation, which lead to greater soil water moisture throughout the growing season [42]. 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 [39, 43]. However, Zhang et al [44] found that NTS reduced leaf water potential by 11% compared to T. This discrepancy is likely 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 [45], 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[46]. In this study, NTS, TP, and NTP reduced the soil-root water potential gradient in the 30-50 cm soil layer at flowering of wheat. No-till with straw cover, TP, and NTP

Peer-reviewed version available at Agronomy 2019, 9, 583; doi:10.3390/agronomy9100583

significantly decreased the root-leaf water potential gradient compared to T at the 0-10 cm soil layer at the seedling stage and 30-50 cm soil layer at flowering. These treatments also significantly reduced the soil-leaf water potential gradient at the 0-10 cm soil layer at the seedling stage and 30-50 cm soil layer at flowering, 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 [47]. In this study, NTS, TP, and NTP reduced 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 [48]. 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 transpiration and net photosynthetic rate of wheat at flowering compared to T, as shown in previous studies [49-51]. The net photosynthetic rate of wheat flag leaves has been reported as 24 to 39% higher with NTS compared to conventional tillage, and also have a significantly higher transpiration rate [49, 52]. In contrast, Jiang et al.[53] 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

Peer-reviewed version available at Agronomy 2019, 9, 583; doi:10.3390/agronomy9100583

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 [54]. 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 [21, 42, 55].

Biomass yield of wheat was significantly greater with NTS, TP, and NTP compared to T. Garofalo and Rinaldi [56] found that a greater rate of transpiration was associated with greater BY. However, Dam et al. [57] found that 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. [58] found that plastic mulching increased BY of maize. This could be due to enhanced crop growth resulting from greater soil temperature [59, 60], soil moisture [58], and radiation capture [61] 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 semiarid Loess Plateau of China [25, 62]. However, Pittelkow et al. [15] found that conservation tillage practices did not increase GY of cereals in moist regions. This is likely because the impact of

Peer-reviewed version available at *Agronomy* **2019**, *9*, 583; doi:10.3390/agronomy9100583

conservation tillage on yield varies among climatic zones. The improvement of wheat GY and WUEg with NTS, TP, and NTP compared to T in this study is attributed to increased water potential and decreased water potential gradient and water transfer resistance, thus enhancing transpiration and BY.

5. Conclusion

This study demonstrates 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 lead to increases in transpiration rate, transpiration, and biomass yield. These results demonstrate that NTS, TP, and NTP are suitable tillage practices for sustainable intensification of wheat production in semi-arid areas.

Author Contributions: Conceptualization, Lingling Li; Data curation, Zhengkai Peng; Formal analysis, Zhengkai Peng, Linlin Wang and Zhuzhu Luo; Funding acquisition, Lingling Li; Investigation, Linlin Wang; Methodology, Junhong Xie and Zhuzhu Luo; Project administration, Junhong Xie; Supervision, Lingling Li and Renzhi Zhang; Validation, Junhong Xie; Writing – original draft, Zhengkai Peng; Writing – review & editing, Lingling Li, Jeffrey A. Coulter, Renzhi Zhang, Jana Kholova and Sunita Choudhary.

Funding: This work was supported by the National Natural Science

Peer-reviewed version available at *Agronomy* **2019**, *9*, 583; doi:10.3390/agronomy9100583

Foundation of China (31761143004 and 31660373), the Department of Education of Gansu Province (2017C-12), and the Research Program of the Gansu Provincial Key Laboratory of Aridland Crop Science, Gansu Agricultural University (GSCS-2017-4).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wei T, Dong Z, Zhang C, et al. Effects of rainwater harvesting planting combined with deficiency irrigation on soil water use efficiency and winter wheat (Triticum aestivum L.) yield in a semiarid area [J]. Field Crops Research, 2018, 218, 231-242.
2. Li F M, Wang J, Xu J Z, et al. Productivity and soil response to plastic film mulching durations for spring wheat on entisols in the semiarid Loess Plateau of China [J]. Soil & Tillage Research, 2004, 78(1): 9-20.
3. Wu J, Miao C, Tang X, et al. A nonparametric standardized runoff index for characterizing hydrological drought on the Loess Plateau, China [J]. Global and planetary change, 2018, 161, 53-65.
4. Zhang S, Sadras V, Chen X, et al. Water use efficiency of dryland wheat in the Loess Plateau in response to soil and crop management [J]. Field Crops Research, 2013, 151(9): 9-18.
5. Deng X P, Lun S, Zhang H, et al. Improving agricultural water use efficiency in arid and semiarid areas of China [J]. Agricultural Water Management, 2006, 80(1): 23-40.
6. Huang Y, Chen L, Bojie F U, et al. The wheat yields and water-use efficiency in the Loess Plateau: straw mulch and irrigation effects [J]. Agricultural Water Management, 2005, 72(3): 209-222.
7. Wang Y, Xie Z, Malhi S S, et al. Effects of rainfall harvesting and mulching technologies on water use efficiency and crop yield in the semi-arid Loess Plateau, China [J]. Agricultural Water Management, 2009, 96(3): 374-382.
8. Yeboah S, Zhang R, Cai L, et al. Greenhouse gas emissions in a spring wheat–field pea sequence under different tillage practices in semi-arid Northwest China [J]. Nutrient Cycling in Agroecosystems, 2016, 106(1): 77-91.
9. Wang L, Palta J A, Wei C, et al. Nitrogen fertilization improved water-use efficiency of winter wheat through increasing water use during vegetative rather than grain filling [J]. Agricultural Water Management, 2018, 197, 41-53.
10. Unkovich M, Baldock J, Farquharson R. Field measurements of bare soil evaporation and crop transpiration, and transpiration efficiency, for rainfed grain crops in Australia–A review [J]. Agricultural water management, 2018, 205, 72-80.
11. Fu A, Chen Y, Li W, et al. Research advances on plant water potential under drought and salt stress [J]. Journal of Desert Research, 2005, 25(05): 744-749.

Peer-reviewed version available at *Agronomy* **2019**, *9*, 583; doi:10.3390/agronomy9100583

12. Kang S. Distribution of hydraulic resistance and water potential in soil-plant-atmosphere continuum [J]. Journal of Hydraulic Engineering, 1990.
13. Yang X G, Liu H L, Hu-Ning Y U. The changing of water transfer potential in soil-plant-atmosphere continuum system of maize field [J]. Chinese Journal of Eco-Agriculture, 2003, 11(1): 27-29.
14. Kalapos T. Leaf water potential-leaf water deficit relationship for ten species of a semiarid grassland community [J]. Plant & Soil, 1994, 160(1): 105-112.
15. Pittelkow C M, Liang X Q, Linquist B A, et al. Productivity limits and potentials of the principles of conservation agriculture [J]. Nature, 2015, 517(7534): 365.
16. Young D L, Schillinger W F. Wheat farmers adopt the undercutter fallow method to reduce wind erosion and sustain profitability [J]. Soil & Tillage Research, 2012, 124(4): 240-244.
17. Tan C, Cao X, Yuan S, et al. Effects of Long-term Conservation Tillage on Soil Nutrients in Sloping Fields in Regions Characterized by Water and Wind Erosion [J]. Scientific Reports, 2015, 5, 17592.
18. Wu J, Cai L Q, Luo Z Z, et al. Effects of conservation tillage on soil physical properties of rainfed field of the Loess Plateau in Central of Gansu [J]. Journal of Soil & Water Conservation, 2014, 28(2): 112-117.
19. Peng Z K, Li L L, Xie J H, et al. Effects of conservational tillage on water characteristics in dryland farm of central Gansu,Northwest China [J]. Chinese Journal of Applied Ecology, 2018, 29(12): 4022-4028.
20. Bescansa P, Imaz M J, Virto I, et al. Soil water retention as affected by tillage and residue management in semiarid Spain [J]. Soil & Tillage Research, 2006, 87(1): 19-27.
21. Cai L Q, Luo Z Z, Zhang R Z, et al. Effect of Different Tillage Methods on Soil Water Retention and Infiltration Capability of Rainfed Field [J]. Journal of Desert Research, 2012, 32(5): 1362-1368.
22. Shao Y, Xie Y, Wang C, et al. Effects of different soil conservation tillage approaches on soil nutrients, water use and wheat-maize yield in rainfed dry-land regions of North China [J]. European Journal of Agronomy, 2016, 81, 37-45.
23. Brunel N, Seguel O, Acevedo E. Conservation tillage and water availability for wheat in the dryland of central Chile [J]. Journal of Soil Science & Plant Nutrition, 2013, 13(3): 622-637.
24. Li L L, Huang G B, Zhang R Z, et al. Effects of no-till with stubble retention on soil water regimes in rainfed areas [J]. Journal of Soil and Water Conservation, 2005, 19(05): 96-8+118.
25. Su Z, Zhang J, Wu W, et al. Effects of conservation tillage practices on winter wheat water-use efficiency and crop yield on the Loess Plateau, China [J]. Agricultural Water Management, 2007, 87(3): 307-314.
26. Yin W, Yu A Z, Chai Q, et al. Wheat and maize relay-planting with straw covering increases water use efficiency up to 46% [J]. Agronomy for Sustainable Development, 2015, 35(2): 815-825.
27. Tao Z, Li C, Li J, et al. Tillage and straw mulching impacts on grain yield and water use efficiency of spring maize in Northern Huang–Huai–Hai Valley [J]. The Crop Journal, 2015, 3(5): 445-450.
28. Gong Z. Chinese soil taxonomy [M]. Science press, 2001.
29. FAO. Soil map of the world: revised legend. World Soil Resources Report 60. Food and

Peer-reviewed version available at *Agronomy* **2019**, *9*, 583; doi:10.3390/agronomy9100583

Agriculture Organization of the United Nations, Rome. [J]. 1990.

30. Zhu X, LI Y, Peng X, et al. Soils of the loess region in China [J]. Geoderma, 1983, 29(3): 237-255.
31. Gubiani P I, Reichert J M, Campbell C, et al. Assessing errors and accuracy in dew-point potentiometer and pressure plate extractor meaurements [J]. Soil Science Society of America Journal, 2013, 77(1): 19-24.
32. Luo T, Wu J. Analysis of The Moisture Transmission Resistance of Corn and the Distribution Characteristics of Stomatal Morphological Index of Leaves under Drip Irrigation [J]. Water saving irrigation, 2018, 8, 19-29.
33. O'Kelly B C. Accurate determination of moisture content of organic soils using the oven drying method [J]. Drying Technology, 2004, 22(7): 1767-1776.
34. Plauborg F. Evaporation from bare soil in a temperate humid climate—measurement using micro-lysimeters and time domain reflectometry [J]. Agricultural & Forest Meteorology, 1995, 76(1): 1-17.
35. Eberbach P, Humphreys E, Kukal S. The effect of rice straw mulch on evapotranspiration, transpiration and soil evaporation of irrigated wheat in Punjab, India [J]. Agricultural Water Management, 2011, 98(12): 1847-1855.
36. Bittelli M. Measuring soil water potential for water management in agriculture: a review [J]. Sustainability, 2010, 2(5): 1226-1251.
37. Tinus R W. Root growth potential as an indicator of drought stress history [J]. Tree Physiology, 1996, 16(9): 795-799.
38. AL-Darby A M, Lowery B, Daniel T C. Corn leaf water potential and water use efficiency under three conservation tillage systems [J]. Soil & Tillage Research, 1987, 9(3): 241-254.
39. Zhang M, Zhang R Z, Cai L Q. Leaf water potential of spring wheat and field pea under different tillage patterns and its relationships with environmental factors [J]. Chinese Journal of Applied Ecology, 2008, 19(7): 1467-1474.
40. Salem H M, Valero C, Muñoz M Á, et al. Short-term effects of four tillage practices on soil physical properties, soil water potential, and maize yield [J]. Geoderma, 2015, 237-238(s 237–238): 60-70.
41. Zhu W, Wang J. Surface Mulching and Conservation of Soil Water [J]. Research of Soil & Water Conservation, 1996, 3(3): 141-145.
42. Peng Z K, Li L L, Xie J H, et al. Effects of different tillage practices on water consumption structure and water use efficiency during crop growth period in arid farmland [J]. Journal of Soil and Water Conservation 2018, 32(05): 214-221.
43. Wang K P, Zhang R Z, Dong B, et al. Effect of long-term conservation tillage on soil water regimes and leaf water potential of crops in rainfed areas of the Loess Plateau [J]. Acta Ecologica Sinica, 2014, 34(13): 3752-3761.
44. Zhang B, Zhang T L, Zhao Q G. Relationship between water potentials of red soiland crop leaves under five farming systems andtheir responses to drought stress in dry season [J]. Acta Pedologica Sinica, 1999, 36(1): 101-110.
45. Li L L, Huang G B, Zhang R Z, et al. Effects of conservation tillage on soil water regimes in rainfed areas [J]. Acta Ecologica Sinica, 2005, 25(09): 2326-2332.
46. Li Q, Chen Y, Liu M, et al. Water potential characteristics and yield of summer maize in different planting patterns [J]. Plant Soil and Environment, 2008, 54(1): 14-19.

Peer-reviewed version available at Agronomy 2019, 9, 583; doi:10.3390/agronomy9100583

47. Liu C M. Study on interface processes of water cycle in soil-plant-atmosphere continuum [J]. Acta Geographica Sinica, 1997, 4, 366-373.
48. Zhang M J, Li L L, Xie J H, et al. Effects of tillage practices on root spatial distribution and yield of spring wheat and pea in the dry land farming areas of central Gansu,China [J]. Chinese Journal of Applied Ecology, 2017, 28(12): 3917-3925.
49. Wang J B, Yan C R, Liu E K, et al. Effects of long-term no-tillage with straw mulch on photosynthetic characteristics of flag leaues and dry matter accumulation and translocation of winter wheat in dryland [J]. Journal of Plant Nutrition & Fertilizer, 2015, 21(2): 296-305.
50. Hou X, Jia Z, Han Q, et al. Effects of rotational tillage practices on soil water characteristics and crop yields in semi-arid areas of north-west China [J]. Soil Research, 2011, 49(7): 625-632.
51. Wang J, Lin Q, Ni Y J, et al. Effect of conservation tillage on photosynthetic characteristics and yield of winter wheat in dry land [J]. Journal of Triticeae Crops, 2009, 480-483.
52. Liu N, Yang W X. Photosynthetic Rate and Water Utilization of Rainfed Wheat with Plastic Mulching on the Semiarid Loess Plateau, China [J]. Proceedings of the National Academy of Sciences, India Section B: Biological Sciences, 2018, 1-10.
53. Jiang X, Yun W, Hou L, et al. Effects of minimum tillage and no-tillage systems on photosynthetic characteristics at late growth stages of winter wheat [J]. Transactions of the Chinese Society of Agricultural Engineering, 2006, 22(5): 66-69.
54. Unkovich M, Baldock J, Farquharson R. Field measurements of bare soil evaporation and crop transpiration, and transpiration efficiency, for rainfed grain crops in Australia – A review [J]. Agricultural Water Management, 2018, 205, 72-80.
55. Wang X J, Huang G B, Li Q P, et al. Characteristics of the evapotranspiration and its yield performance of rainfed spring wheat and peas fileds [J]. journal of Arid Land Resources and Environment 2010, 24(05): 172-177.
56. Garofalo P, Rinaldi M. Water-use efficiency of irrigated biomass sorghum in a Mediterranean environment [J]. Spanish Journal of Agricultural Research, 2013, 11(4): 1153-1169.
57. Dam R F, Mehdi B B, Burgess M S E, et al. Soil bulk density and crop yield under eleven consecutive years of corn with different tillage and residue practices in a sandy loam soil in central Canada [J]. Soil & Tillage Research, 2005, 84(1): 41-53.
58. Zhang S, Li P, Yang X, et al. Effects of tillage and plastic mulch on soil water, growth and yield of spring-sown maize [J]. Soil and Tillage Research, 2011, 112(1): 92-97.
59. Anikwe M A N, Mbah C N, Ezeaku P I, et al. Tillage and plastic mulch effects on soil properties and growth and yield of cocoyam (Colocasia esculenta) on an ultisol in southeastern Nigeria [J]. Soil & Tillage Research, 2007, 93(2): 264-272.
60. Li X Y, Gong J D, Gao Q Z, et al. Incorporation of ridge and furrow method of rainfall harvesting with mulching for crop production under semiarid conditions [J]. Agricultural Water Management, 2001, 50(3): 173-183.
61. Liu Y, Yang S, Li S, et al. Growth and development of maize (Zea mays L.) in response to different field water management practices: Resource capture and use efficiency [J]. Agricultural & Forest Meteorology, 2010, 150(4): 606-613.
62. Jin H, Wang Q, Li H, et al. Effect of alternative tillage and residue cover on yield and water

Peer-reviewed version available at *Agronomy* **2019**, *9*, 583; doi:10.3390/agronomy9100583

use efficiency in annual double cropping system in North China Plain [J]. Soil & Tillage Research, 2009, 104(1): 198-205.

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

Peer-reviewed version available at Agronomy 2019, 9, 583; doi:10.3390/agronomy9100583

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 ≤ DI ≤ 0.35, and DI > 0.35, respectively.

Peer-reviewed version available at Agronomy 2019, 9, 583; doi:10.3390/agronomy9100583

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

Year	Tillage practice[a]	Seedling	Tillering		Jointing		Flowering		
		0–10	0–10	10–30	0–10	10–30	0–10	10–30	30–50
2016	T	−2.60b	−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

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

[a] 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.

Peer-reviewed version available at *Agronomy* **2019**, *9*, 583; doi:10.3390/agronomy9100583

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

Year	Tillage practice[a]	Seedling	Tillering		Jointing		Flowering		
		0–10	0–10	10–30	0–10	10–30	0–10	10–30	30–50
2016	T	−3.06b	−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

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

[a] 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.

Peer-reviewed version available at *Agronomy* **2019**, *9*, 583; doi:10.3390/agronomy9100583

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

Year	Tillage practice[a]	Seedling	Tillering	Jointing	Flowering
2016	T	−7.19c	−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

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

[a] 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.

Peer-reviewed version available at Agronomy 2019, 9, 583; doi:10.3390/agronomy9100583

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

Year	Tillage practice[a]	Seedling	Tillering		Jointing		Flowering		
		0–10	0–10	10–30	0–10	10–30	0–10	10–30	30–50
2016	T	0.46a	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

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

[a] 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.

Peer-reviewed version available at *Agronomy* **2019**, *9*, 583; doi:10.3390/agronomy9100583

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

Year	Tillage practice[a]	Seedling	Tillering		Jointing		Flowering		
		0–10	0–10	10–30	0–10	10–30	0–10	10–30	30–50
2016	T	4.13a	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

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

[a] 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.

Peer-reviewed version available at *Agronomy* **2019**, *9*, 583; doi:10.3390/agronomy9100583

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

Year	Tillage practice[a]	Seedling	Tillering		Jointing		Flowering		
		0–10	0–10	10–30	0–10	10–30	0–10	10–30	30–50
2016	T	4.59a	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

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

[a] 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.

Peer-reviewed version available at *Agronomy* **2019**, *9*, 583; doi:10.3390/agronomy9100583

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[a]	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	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

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

[a] 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.

Peer-reviewed version available at Agronomy 2019, 9, 583; doi:10.3390/agronomy9100583

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 layer (cm)	Water potential index[a]	Transpiration	Biomass yield	WUE_b	Grain yield	WUE_g
Seeding	0–10	S	0.888**	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	.765**	.735**	.644**	0.465	0.348
		R	.551*	.581*	0.385	0.334	0.121
		S-R	−0.033	−0.085	0.053	−0.019	0.118
		R-L	−.590**	−.489*	−0.315	−.557*	−0.36
		S-L	−.526*	−.472*	−0.236	−.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

Peer-reviewed version available at Agronomy 2019, 9, 583; doi:10.3390/agronomy9100583

	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*

Correlation coefficients followed by * and ** are significant at $P \leq 0.05$ and 0.01, respectively.

[a]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.

Figure captions

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

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.

Peer-reviewed version available at Agronomy 2019, 9, 583; doi:10.3390/agronomy9100583

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 ≤ 0.05). Error bars denote standard errors of the means (n = 4).

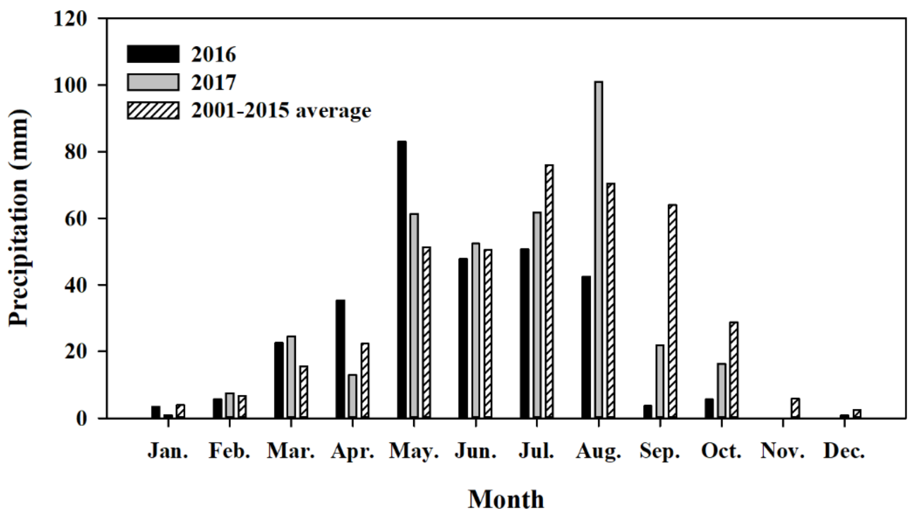

Figure 1. Monthly total precipitation for 2016, 2017, and the 2001-2015 average at the study area.

Peer-reviewed version available at Agronomy 2019, 9, 583; doi:10.3390/agronomy9100583

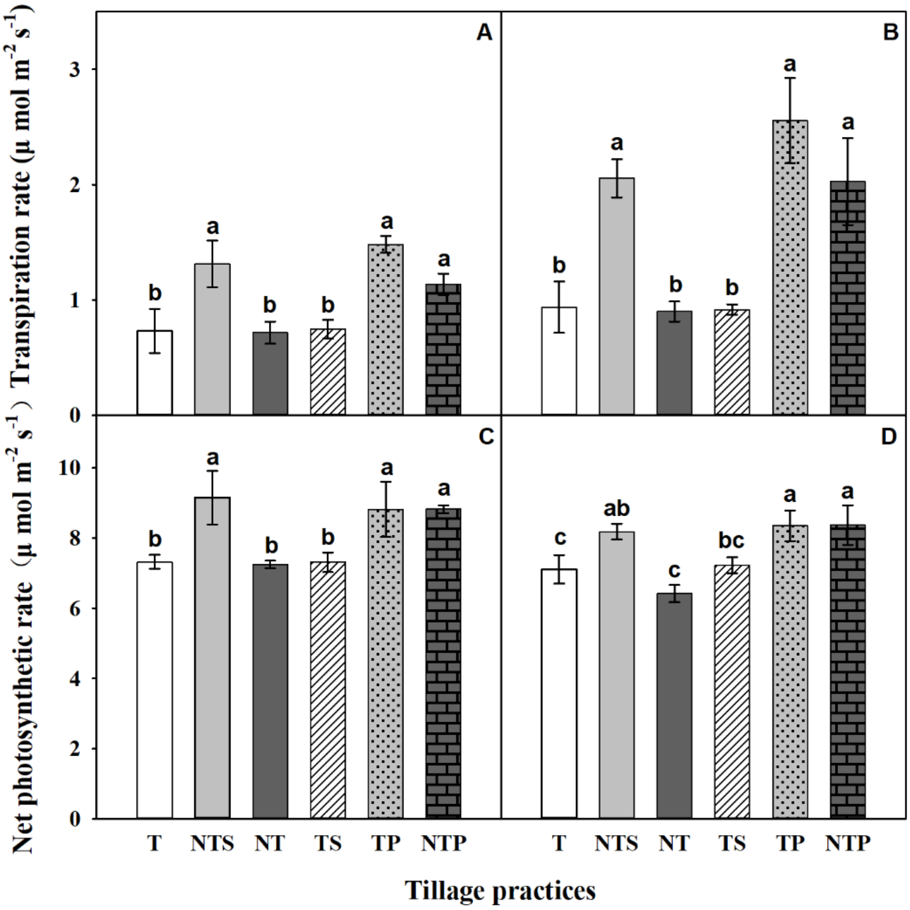

Figure 2. Transpiration rate at the flowering stage of wheat in 2016 (A) and 2017 (B) and net photosynthetic rate at the flowering stage of wheat in 2016 (C) and 2017 (D) as affected by tillage practice. T, conventional tillage with no straw; NTS, no-till with straw cover; NT, no-till with no straw; 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 ($n = 4$).

Peer-reviewed version available at Agronomy 2019, 9, 583; doi:10.3390/agronomy9100583

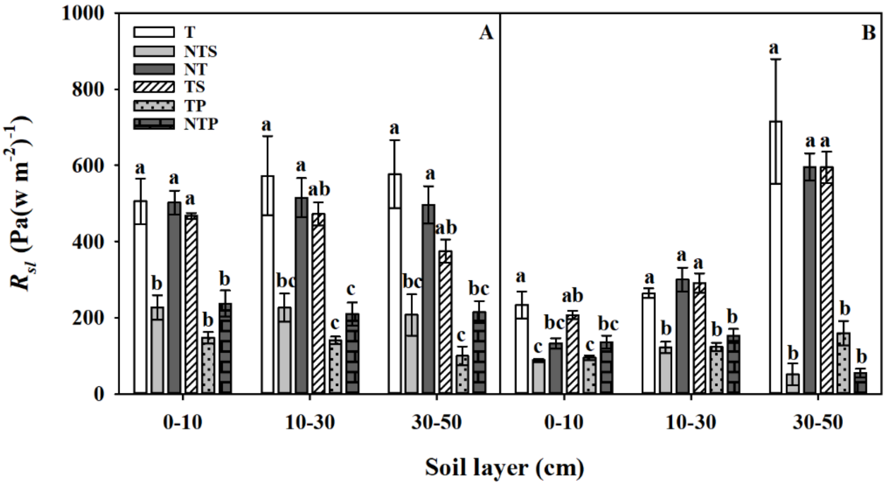

Figure 3. Soil-leaf water transfer resistance (R_{sl}) at the flowering stage of wheat in 2016 (A) and 2017 (B) as affected by tillage practice for different soil layers. T, conventional tillage with no straw; NTS, no-till with straw cover; NT, no-till with no straw; TS, conventional tillage with straw 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).