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Effects of ridge tillage and mulching on water availability, grain yield, and water use efficiency in rain-fed winter wheat under different rainfall and nitrogen conditions

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ABSTRACT

Tillage practices which improve water availability and water use efficiency (*WUE*) are beneficial for rain-fed agriculture. However, there is little consensus about the effects of ridge tillage and mulching, combined with different rainfall and N fertilization conditions, on water status and productivity in winter wheat fields. The current study aimed to investigate the effects of ridge tillage and mulching on water availability, grain yield, and *WUE* in rain-fed winter wheat under different rainfall and N conditions. A three-year field experiment was conducted during 2011–2014 following a split-split plot design. The experiment included two humid growing seasons (2011–2012 and 2013–2014) and one dry growing season (2012–2013). Nitrogen application rates were 0 and 180 kg N ha^{-1}. Tillage systems included conventional tillage (CT, as control), stalk mulching (SM), film mulching (FM), ridge tillage without mulch (RT), ridge tillage with film on ridges (RTf), and ridge tillage with film on ridges and stalk in furrows (RTfs). Results showed that averaged across growing seasons and N treatments, ridge tillage and mulching decreased evapotranspiration by 8.3%–16.2%, and increased grain yield and *WUE* by 4.2%–15.2% and 16.7%–36.8% compared with CT, respectively. Ridge tillage and mulching tended to increase grain yield especially when rainfall was deficient, and tended to increase *WUE* especially when N supply was deficient. Spike number per hectare and grain number per spike made significant contributions to grain yield when all three yield components were considered. Ridge tillage and mulching tended to increase mass-based and area-based canopy moisture during regreening (stage 6 in Feekes scale, late Feb–early Mar) to grain-filling stage (middle May) which was positively correlated with grain yield. Lower leaf area index (*LAI*) in ridge tillage and mulching treatments led to grain yield loss, but the loss was alleviated by greater total chlorophyll in flag leaves. Overall, ridge tillage and mulching improved water availability, grain yield, and *WUE* in rain-fed winter wheat, especially when N and rainfall were deficient.

1. Introduction

Climate change could potentially threaten world food security (Wheeler and von Braun, 2013). Especially under these conditions, crop production is highly dependent on freshwater supply. Drought and periodical rainfall shortage (such as shortage at anthesis) limit grain yields and water use efficiency (*WUE*) in cereal crops such as winter wheat, especially in rain-fed regions (Seddaiu et al., 2016). With limited freshwater resources and high irrigation costs, large areas of wheat are planted under rain-fed conditions. Therefore, it is important to improve water availability and *WUE* in rain-fed winter wheat with water saving and conservation practices (Liu et al., 2016).

As tillage practices affect soil properties such as soil structure and moisture, negative effects of drought and periodical rainfall shortage will be alleviated by improved tillage practices (Liu et al., 2013). Rainfall harvesting techniques such as ridge tillage have been proposed to increase soil water content by enhancing infiltration (Liu et al., 2014); while mulching techniques such as plastic-film mulching have been proposed to improve water availability in soils, mainly by reducing evapotranspiration (Diaz-Hernandez and Salmeron, 2012). Ridge tillage and mulching also affect other soil properties besides moisture, such as soil temperature and mineralization, which further affect crop traits such as leaf area index and grain yields (Liu and Wiatrak, 2012; Shi et al., 2012). Previous studies showed that ridge tillage and

Abbreviations: CT, conventional tillage; SM, stalk mulching; FM, film mulching; RT, ridge tillage without mulch; RTf, ridge tillage with film on ridges; RTfs, ridge tillage with film on ridges and stalk in furrows; *WUE*, water use efficiency; *LAI*, leaf area index

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mulching increase yields and *WUE* in rain-fed crops (Liu and Siddique, 2015; Wang et al., 2016), while stalk mulching also enhances soil quality (Kahlon et al., 2013). Overall, application of improved tillage practices (such as ridge tillage and mulching) is beneficial for sustainable development of rain-fed agriculture.

The southern Loess Plateau is a major winter wheat production region in China, with drought and periodical rainfall shortage as major limiting factors. High rainfall variability and evaporation lead to an imbalance between water supply and plant water demands, which then result in lower grain yields (Yang et al., 2017; Seddaiu et al., 2016). To alleviate the negative effects of drought and periodical rainfall shortage on crop production, ridge tillage and mulching have been proposed to rain-fed regions (Liu et al., 2014; Wang et al., 2016). For example, Zhang et al. (2011) reported a combination of ridge tillage and mulching, i.e., ridge tillage with film on ridges and stalk in furrows (RTfs), is an efficient measure to increase crop yield and improve soil fertility in the Loess Plateau of China.

Although ridge tillage and mulching provide an opportunity of sustainably enhancing crop productivity in rain-fed regions, performances of these techniques are inconsistent in different regions and growing seasons, partly due to influences from other factors such as rainfall and fertilization (Wang et al., 2016). For example, film mulching has more notable effects on soil water content and crop yield when water supply is deficient (Diaz-Hernandez and Salmeron, 2012; Wang et al., 2016), while mulching treatments have more significant effects on *WUE* when supplied with deficient N (Li et al., 2015). Therefore, factors such as rainfall and N fertilization should be considered when investigating the performances of ridge tillage and mulching. However, for rain-fed winter wheat in the southern Loess Plateau, there is little consensus about the effects of ridge tillage and mulching on water availability, grain yield, and *WUE* under different rainfall and N conditions.

The study aimed to: i) assess the effects of ridge tillage, mulching, and their combination on water availability, grain yield, and *WUE* in rain-fed winter wheat under different rainfall and N conditions; ii) elucidate the mechanism of improvements in grain yield and *WUE* in ridge tillage and mulching treatments, based on data of yield components, water availability, leaf area index, and leaf chlorophyll.

2. Materials and methods

2.1. Site and materials

Before the current study, a wheat (*Triticum aestivum* L.) - maize (*Zea mays* L.) rotation had been conducted for two years (Oct 5th, 2009–Oct 7th, 2011) without fertilization and without irrigation. The current three-year field experiment was conducted during 2011–2014 wheat growing seasons, i.e., Oct 8th, 2011–Jun 7th, 2012 (244 d); Oct 6th, 2012–May 27th, 2013 (234 d); and Oct 9th, 2013–Jun 6th, 2014 (241 d). While between wheat growing seasons, i.e., Jun 8th, 2012–Oct 5th, 2012 and May 28th, 2013–Oct 8th, 2013, maize was planted without fertilization and irrigation. The experimental site was located in Yangling (34°17′ N, 108°04′ E; 520 m ASL), in the southern Loess Plateau of China. The mean annual precipitation is about 550–600 mm, with about 200–250 mm occurring during the wheat growing season; the annual mean temperature is about 13 °C. During 2011–2012, 2012–2013, and 2013–2014 wheat growing season, rainfall totaled 242.9, 191.8, and 266.7 mm; daily air temperature averaged 8.2 °C (lowest: –7.0 °C; highest: 25.3 °C), 8.0 °C (lowest: –7.3 °C; highest: 26.0 °C), and 8.3 °C (lowest: –6.0 °C; highest: 24.5 °C), respectively (Fig. 1). The soil was classified as an Anthropic Torrifluvents Entisol (Soil Survey Staff, 2014). Selected properties of the top layer (0–20 cm) were: bulk density 1.33 Mg m^{-3}, clay content 165 g kg^{-1}, silt content 517 g kg^{-1}, sand content 318 g kg^{-1}, organic C 9.83 g kg^{-1}, total N 0.88 g kg^{-1}, total P 0.59 g kg^{-1}, total K 1.86 g kg^{-1}, inorganic N 7.02 mg kg^{-1}, Olsen P 8.63 mg kg^{-1}, available K 130.61 mg kg^{-1}, soil pH (1:2.5 soil:water, w:v) 8.3, and field capacity 244 g kg^{-1}. The groundwater depth was 25–40 m.

Nitrogen fertilizer was urea (46.4% N). Phosphorus fertilizer was calcium superphosphate (16% P_2O_5). Plastic film was made of transparent polyethylene, 0.001 cm thick. Maize stalks were cut into pieces before mulching, with selected properties as: average length 3 cm; total N 10.5 g kg^{-1}, total P 13.7 g kg^{-1}, and total K 9.6 g kg^{-1}. Wheat cultivar was *Triticum aestivum* L. 'Xiaoyan 22'.

2.2. Experimental design

Treatments followed a split-split plot design with three replications (Fig. 2), which was suitable for analysis of three factors (Yang et al., 2015). Growing seasons included two humid growing seasons (2011–2012 and 2013–2014) and one dry growing season (2012–2013) (Fig. 1). Tillage systems included conventional tillage (CT, as control), stalk mulching (SM), film mulching (FM), ridge tillage without mulch (RT), ridge tillage with film on ridges (RTf), and ridge tillage with film on ridges and stalk in furrows (RTfs). Nitrogen application rates were 0 (N0) and 180 kg N ha^{-1} (N180). The experiment consisted of 36 plots each growing season, with a size of 4 × 4 m^2 for each plot (Fig. 2).

Plots were plowed using a rotary cultivator to 20 cm depth before sowing. In FM, both film and planted rows were 30 cm wide. In RT, RTf, and RTfs, ridges were 15 cm in height, while ridges and planted rows were both 30 cm wide. In SM, each plot was mulched with stalk at 5.0 Mg ha^{-1}. In RTf, ridges were mulched with film. In RTfs, ridges were mulched with film while planted rows mulched with stalk at 2.5 Mg ha^{-1} (Fig. 2).

Fertilizers were applied before sowing as a basal fertilization. Phosphorus fertilizer was applied at 120 kg P_2O_5 ha^{-1} in all treatments. Nitrogen fertilizer was applied at 180 kg N ha^{-1} in the N180 treatments. In CT and SM, fertilizers were broadcasted and then incorporated into 0–15 cm soil layers; while in other tillage systems, fertilizers were applied by deep-band application to a 15 cm depth under film or ridges (Fig. 2).

After applying fertilizers, wheat was sown to 5 cm depth at 120 kg ha^{-1}. In CT and SM, wheat was sown in planting rows with 20 cm spacing consistent with local growers, while in other tillage systems, with 30 cm spacing, i.e., much wider so as to establish ridges or film mulching (Fig. 2). No side-dress fertilizer or irrigation was applied.

2.3. Sampling and lab analyses

Stem density (*SD*, stems m^{-2}) was determined by counting stems in a 1 × 1 m^2 area in the middle of each plot at grain-filling stage (middle May). Then, 20 stems were randomly collected in each treatment, and leaf area per stem (cm^2 stem^{-1}) was measured using ImageJ (Martin et al., 2013). Besides, 10 flag leaves were collected from each plot, cut into pieces, and mixed as a single sample for analysis of total chlorophyll (Fiorini et al., 2016). Leaf area index (*LAI*) was given as:

$$LAI = LAPS * SD * 10^{-4} \tag{1}$$

where, *LAPS* is leaf area per stem (cm^2 stem^{-1}); 10^{-4} is used to convert cm^2 stem^{-1} to m^2 stem^{-1}.

At maturity (late May–early Jun), a 1 × 1 m^2 area was harvested in the middle of each plot to determine grain yield and spike number per hectare (Yao et al., 2007). Wheat samples were threshed using a cereal thresher. Both straw and grain samples were dried at 105 °C for 30 min, then at 80 °C to a constant weight. Grain yields were adjusted to 14% moisture. Grain number per spike was determined based on data from 20 spikes in each treatment. Thousand grain weight was measured with an automatic counting machine (n = 3).

Both at the beginning and the end of each growing season, soil was sampled at 0–200 cm depth (20 cm layer intervals) with a 25-mm

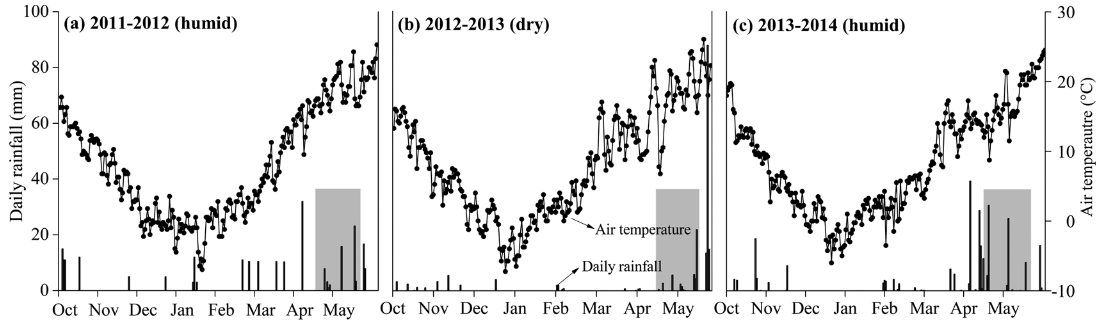

Fig. 1. Daily rainfall and air temperature during 2011–2014 wheat growing seasons. 2011–2012 and 2013–2014 are humid growing seasons as rainfall totaled 242.9 and 266.7 mm, with 81.2 and 131.9 mm occurring during flowering to grain-filling (about Apr 15th–May 30th, showed as the grey area), respectively. 2012–2013 is a dry growing season as rainfall totaled 191.8 mm, with only 45.3 mm occurring during flowering to grain-filling. It should be mentioned that heavy rainfall events (116.2 mm) occurred at maturity (after grain-filling) in the 2012–2013 growing season.

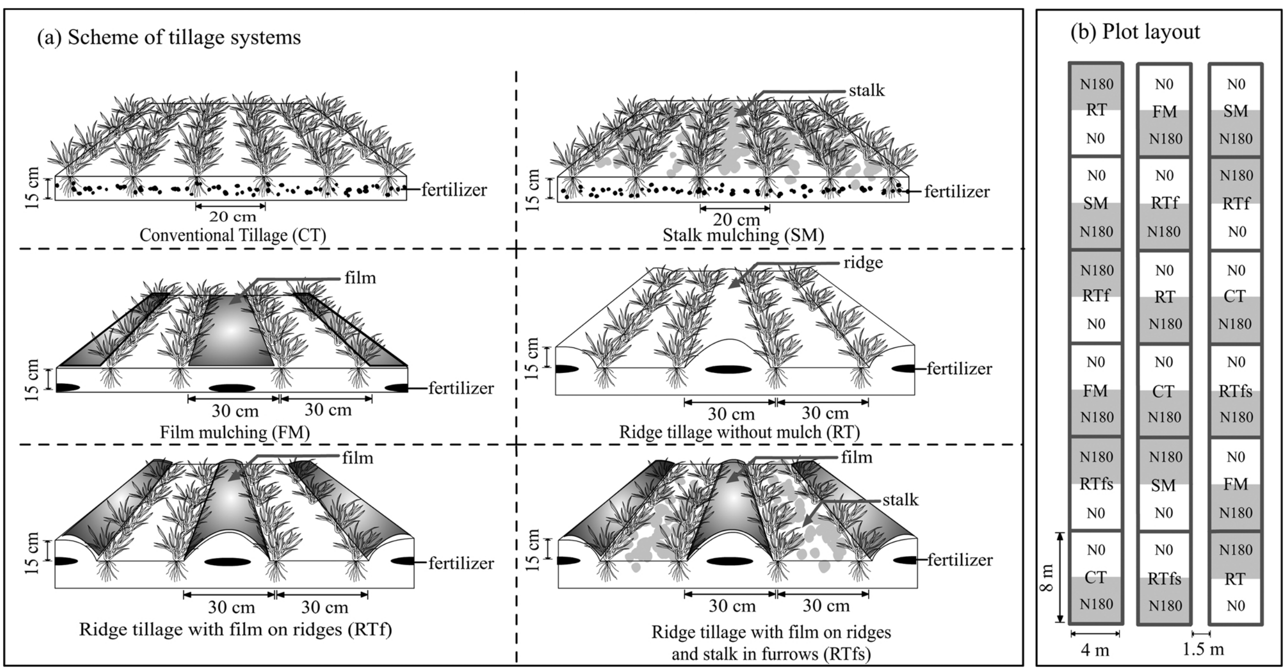

Fig. 2. Scheme of tillage systems (a) and plot layout (b). Tillage plots were split into two nitrogen fertilization subplots, i.e., N0 (0 kg N ha^{-1}) and N180 (180 kg N ha^{-1}).

diameter soil probe. For each plot, three samples were collected and soil samples of the same layer were mixed thoroughly, and then sent to the laboratory for measurement of soil water content. Briefly, soil samples of each layer were weighed wet, thereafter dried in an oven at 105 °C until soil weight became constant, and then weighed again to determine bulk density (Ferraro and Ghersa, 2007) and soil water content (gravimetric water content). Soil bulk density was multiplied by gravimetric water content to determine the volumetric water content. Soil water storage in the 0–200 cm profile was calculated by multiplying soil profile depth by volumetric water content (Hou et al., 2012). Evapotranspiration (*ET*) and water use efficiency (*WUE*) were given as:

$$ET\ (\text{mm}) = P + \Delta SWS \tag{2}$$

$$WUE\ (\text{kg ha}^{-1}\ \text{mm}^{-1}) = GY\ /\ ET \tag{3}$$

where, *P* is total precipitation each growing season (mm); ΔSWS equals soil water storage in 0–2 m profile at sowing minus that at maturity (mm); *GY* is grain yield (kg ha^{-1}) (Bu et al., 2013). Eq. (2) is a simplified one which does not consider runoff, drainage, and capillary rise, due to low rainfall and great groundwater depth in the region (Wang et al., 2009).

During regreening (stage 6 in Feekes scale, late Feb–early Mar) to maturity (late May–early Jun), wheat was sampled (n = 6 plants for each treatment) at 9:00 to 10:00 a.m. at an interval of about 7 days. Simultaneously, plant density was determined from in a 1 × 1 m^2 area in the middle of each plot. Wheat samples were dried at 105 °C for 30 min, then at 80 °C until plant weight became constant to calculate canopy moisture (Yao et al., 2007) as:

$$MCM = (FW - DW)\ /\ DW * 100\% \tag{4}$$

$$ACM = MCM * 10^{-2} * PB * PD * 10^{-3} \tag{5}$$

where, *MCM* is mass-based canopy moisture (%); *FW* is fresh weight (g); *DW* is dry weight (g); *ACM* is area-based canopy moisture (mm); *PB* is plant biomass (g $plant^{-1}$); *PD* is plant density (plants m^{-2}); 10^{-2} is used to convert % to g g^{-1}; 10^{-3} is used to convert g m^{-2} to mm.

2.4. Statistical analyses

Data were evaluated by analysis of variance (ANOVA) for split-split plot design (Yang et al., 2015). Means were compared using Tukey's studentized range test (α = 0.05). Correlation analysis (CA) was performed to analyze the relationship between canopy moisture and grain yield (using original data). Multiple regression (MR) analysis was performed to investigate the contributions of yield components to grain yield as:

$$GY = \mathrm{a} + \mathrm{b}\cdot SNPH + \mathrm{c}\cdot GNPS + \mathrm{d}\cdot TGW \quad (6)$$

where, GY is grain yield; $SNPH$ is spike number per hectare; $GNPS$ is grain number per spike; TGW is thousand grain weight; a is the intercept; b, c, and d are regression coefficients, which showed the contribution of each yield component on grain yield when all yield components were considered (Moore et al., 2009). Data of grain yield and yield components were normalized before MR analysis as:

$$x_n = (x_o - xmin) / (xmax - xmin) \quad (7)$$

where, x_n is the normalized value; x_o is the original value; $xmin$ is the minimum value; $xmax$ is the maximum value (Yang et al., 2015). Response surface (RS) analysis was used to investigate the effects of leaf area index and total chlorophyll in flag leaf on grain yield as:

$$Z = \mathrm{A} + \mathrm{B}\cdot X + \mathrm{C}\cdot Y + \mathrm{D}\cdot X^2 + \mathrm{E}\cdot Y^2 + \mathrm{F}\cdot X\cdot Y \quad (8)$$

where, Z is grain yield; X is leaf area index; Y is total chlorophyll in flag leaf; A is the intercept; B, C, D, E, and F are regression coefficients (Han et al., 2013). The ANOVA, CA, MR, and RS were conducted using SAS 9.1 (SAS Institute Inc., NC, US).

3. Results

3.1. General results of ANOVA

Table 1 shows that evapotranspiration (*ET*), leaf area index (*LAI*), and total chlorophyll in flag leaf (*TChl*) were significantly affected by season, tillage, N, and their interactions. Grain yield (*GY*), spike number per hectare (*SNPH*), and water use efficiency (*WUE*) were significantly affected by season, tillage, N, and season × N. Grain number per spike (*GNPS*) was significantly affected by tillage, N, and season × N. Thousand grain weight (*TGW*) was significantly affected by season, tillage, and season × N ($P < .05$ or $P < .01$).

3.2. Grain yield and yield components

Results of grain yield (Table 2) showed that averaged across N and tillage treatments, grain yield in the dry growing season 2012–2013 (2224 kg ha^{-1}) was 52.6% lower than that in the humid growing season 2011–2012 (4696 kg ha^{-1}) and 56.3% lower than that in the humid growing season 2013–2014 (5090 kg ha^{-1}). Averaged across growing seasons and tillage treatments, grain yield in N180 (5045 kg ha^{-1}) was 70.4% greater than in N0 (2961 kg ha^{-1}) ($P < .05$). Ridge tillage and mulching increased the grand mean of grain yield (averaged across growing seasons and N treatments) by 4.2%–15.2% compared with conventional tillage (CT). Additionally, mulched ridge tillage systems (RTf and RTfs) tended to increase grain yield compared with RT, indicating ridge tillage and mulching had positive interactions on grain yield. Besides, ridge tillage and mulching tended to increase grain yield especially in the dry growing season 2012–2013 rather than in humid growing seasons 2011–2012 and 2013–2014.

Table 1
ANOVA of effects of growing season, tillage, N treatment, and their interaction on evapotranspiration (*ET*), grain yield (*GY*), spike number per hectare (*SNPH*), grain number per spike (*GNPS*), thousand grain weight (*TGW*), leaf area index (*LAI*), total chlorophyll in flag leaf (*TChl*), and water use efficiency (*WUE*).

Factor	*ET*	*GY*	*SNPH*	*GNPS*	*TGW*	*LAI*	*TChl*	*WUE*
Season	**	**	**	*ns*	**	**	**	**
Tillage	**	**	**	**	*	**	**	**
N	**	**	**	**	*ns*	**	**	**
Season × tillage	**	*ns*	*ns*	*ns*	*ns*	*	**	*ns*
Season × N	**	**	**	**	**	**	*	**
Tillage × N	*	*ns*	*ns*	*ns*	*ns*	**	**	*ns*
Season × tillage × N	*	*ns*	*ns*	*ns*	*ns*	*	**	*ns*

ns $P > .05$.
* $P < .05$.
** $P < .01$.

Results presented in Table 3 showed that the effects of ridge tillage and mulching on yield components were inconsistent as affected by N treatments and growing seasons. Averaged across growing seasons and N treatments (grand mean), ridge tillage and mulching tended to increase spike number per hectare (except for RT), grain number per spike, and thousand grain weight (except for SM and FM). A multiple regression analysis showed the contributions of yield components to grain yield as:

$$GY = -0.077 + 0.866\cdot SNPH + 0.326\cdot GNPS + 0.043\cdot TGW \quad (9)$$

where, 0.866 ($P < .01$), 0.326 ($P < .01$), and 0.043 ($P > .05$) are the regression coefficients for *SNPH*, *GNPS*, and *TGW*, respectively; for the model, $P < .01$, $R^2 = 0.972$. The results indicated that *SNPH* and *GNPS* made significant contributions to grain yield when all the three yield components were considered.

Additionally, Table 3 shows that growing season and N fertilization had notable effects on *SNPH* and *GNPS*. For example, averaged across N and tillage treatments, *SNPH* in the dry growing season 2012–2013 (1.94 million spikes ha^{-1}) was 35.1% lower than in the humid growing season 2011–2012 (2.99 million spikes ha^{-1}) and 37.6% lower than in the humid growing season 2013–2014 (3.11 million spikes ha^{-1}) ($P < .05$). Averaged across growing seasons and tillage treatments, *SNPH* in N180 (3.49 million spikes ha^{-1}) was 86.6% greater than that in N0 (1.87 million spikes ha^{-1}) ($P < .05$). According to the grand mean, ridge tillage and mulching (except for RT) tended to increase *SNPH* compared with CT, in which FM significantly increased *SNPH* ($P < .05$); while ridge tillage and mulching (except for SM) significantly increased *GNPS* compared with CT ($P < .05$).

3.3. Evapotranspiration and water use efficiency

Results of evapotranspiration (Table 4) showed that averaged across N and tillage treatments, evapotranspiration in the dry growing season 2012–2013 (242.1 mm) was 31.7% lower than in the humid growing season 2011–2012 (354.5 mm) and 12.9% lower than in the humid growing season 2013–2014 (277.8 mm). Averaged across growing seasons and tillage treatments, evapotranspiration in N180 (308.6 mm) was 12.5% greater than in N0 (274.3 mm). Averaged across growing seasons and N treatments (grand mean), ridge tillage and mulching decreased evapotranspiration by 8.3%–16.2% compared with CT.

Results of water use efficiency (*WUE*, Table 4) showed that averaged across N and tillage treatments, *WUE* in dry growing season 2012–2013 (9.2 kg ha^{-1} mm^{-1}) was 30.3% and 50.5% lower than in humid growing season 2011–2012 (13.2 kg ha^{-1} mm^{-1}) and 2013–2014 (18.6 kg ha^{-1} mm^{-1}), respectively. Averaged across growing seasons and tillage treatments, *WUE* in N180 (16.6 kg ha^{-1} mm^{-1}) was 55.1% greater than in N0 (10.7 kg ha^{-1} mm^{-1}); while averaged across growing seasons and N treatments (grand mean), ridge tillage and mulching increased *WUE* by 16.7%–36.8% compared with CT. Besides, mulched ridge tillage systems (RTf and RTfs) tended to increase *WUE* compared with RT, indicating ridge tillage and mulching had positive interactions on *WUE*.

3.4. Soil water content and canopy moisture

Results of soil water content (Fig. 3) showed that ridge tillage and mulching increased soil water content in 0–80 cm profiles compared with CT in all growing seasons and N treatments. For example, in N180 treatments during the 2011–2012 growing season (Fig. 3d), soil water content in 0–80 cm profiles was 10.6%–11.5% in CT, while it was 12.0%–14.7% in SM, 12.0%–14.3% in FM, 11.5%–13.4% in RT, 11.9%–15.4% in RTf, and 11.6%–14.7% in RTfs. It should be noted that

Table 2
Effects of growing season, tillage, and N treatments on grain yield (kg ha^{-1}).

	N0			N180			Grand mean
	2011–2012	2012–2013	2013–2014	2011–2012	2012–2013	2013–2014	
CT	3342±386^{b}	1175±60^{c}	3703±176^{a}	5418±661^{a}	2737±105^{c}	5855±408^{ab}	3705±1657^{d}
SM	3138±294^{b}	1404±125^{ab}	4138±516^{a}	6023±636^{a}	3086±185^{ab}	6521±807^{ab}	4052±1867^{abc}
FM	4061±423^{a}	1485±109^{a}	4141±209^{a}	6027±223^{a}	3127±176^{ab}	6775±472^{a}	4270±1823^{a}
RT	3653±402^{ab}	1265±92^{bc}	3843±162^{a}	5685±707^{a}	2972±277^{bc}	5752±669^{b}	3862±1643^{cd}
RTf	3654±213^{ab}	1447±201^{ab}	3949±419^{a}	5721±570^{a}	3129±263^{ab}	5975±437^{ab}	3979±1615^{bcd}
RTfs	3500±600^{ab}	1539±93^{a}	3878±368^{a}	6134±242^{a}	3322±173^{a}	6555±504^{ab}	4155±1796^{ab}

Nitrogen application rates are N0 (0 kg N ha^{-1}) and N180 (180 kg N ha^{-1}). Tillage treatments include conventional tillage (CT, as control), stalk mulching (SM), film mulching (FM), ridge tillage without mulch (RT), ridge tillage with film on ridges (RTf), and ridge tillage with film on ridges and stalk in furrows (RTfs). Values are mean ± SD (n = 3). Grand mean is the value averaged across growing seasons and N treatments (n = 18). Means with same letters in the same column are not significantly different (P > .05). Grey background color indicates significant difference between the tillage treatment and CT (P < .05). Averaged across N and tillage treatments, grain yield was 4696 ± 1251^{a}, 2224 ± 873^{b}, and 5090 ± 1264^{a} kg ha^{-1} in 2011–2012, 2012–2013, and 2013–2014 growing season, respectively. Averaged across growing seasons and tillage treatments, grain yield was 2961 ± 1183^{b} and 5045 ± 1504^{a} kg ha^{-1} in N0 and N180 treatment, respectively.

Table 3
Effects of growing season, tillage, and N treatments on spike number per hectare (million spikes ha^{-1}), grain number per spike (grains spike^{-1}), and thousand grain weight (g).

	N0			N180			Grand mean
	2011–2012	2012–2013	2013–2014	2011–2012	2012–2013	2013–2014	
Spike number per hectare (million spikes ha^{-1})							
CT	2.19±0.11^{ab}	1.12±0.20^{b}	2.29±0.21^{a}	3.66±0.12^{c}	2.35±0.56^{a}	4.04±0.29^{ab}	2.61±1.03^{bc}
SM	1.80±0.08^{c}	1.49±0.26^{ab}	1.72±0.29^{b}	4.11±0.12^{b}	2.38±0.50^{a}	4.20±0.23^{a}	2.62±1.18^{b}
FM	2.23±0.07^{a}	1.72±0.57^{a}	2.32±0.29^{a}	4.41±0.05^{a}	2.46±0.44^{a}	4.58±0.65^{a}	2.95±1.20^{a}
RT	2.08±0.06^{ab}	1.29±0.24^{ab}	2.11±0.31^{ab}	3.30±0.16^{d}	2.48±0.48^{a}	3.25±0.42^{b}	2.42±0.77^{c}
RTf	2.15±0.14^{ab}	1.26±0.18^{ab}	2.35±0.09^{a}	4.11±0.16^{b}	2.40±0.57^{a}	4.21±0.50^{a}	2.75±1.13^{b}
RTfs	2.04±0.08^{b}	1.53±0.10^{ab}	2.03±0.32^{ab}	3.85±0.08^{c}	2.77±0.24^{a}	4.24±0.48^{a}	2.74±1.05^{b}
Grain number per spike (grains spike^{-1})							
CT	39.8±8.4^{a}	31.7±0.8^{ab}	40.2±1.8^{a}	38.2±7.6^{a}	33.6±3.2^{a}	38.3±3.5^{b}	36.9±5.4^{c}
SM	44.1±11.9^{a}	30.7±0.8^{ab}	41.5±5.9^{a}	39.0±7.5^{a}	35.1±0.5^{a}	38.8±2.3^{b}	38.2±6.9^{bc}
FM	47.4±10.1^{a}	30.5±0.9^{b}	44.1±5.0^{a}	35.3±9.3^{a}	35.9±5.3^{a}	38.6±3.8^{b}	38.6±8.0^{b}
RT	44.3±7.3^{a}	31.1±2.5^{ab}	44.9±2.8^{a}	42.3±6.6^{a}	34.6±2.9^{a}	44.5±1.5^{a}	40.3±6.7^{a}
RTf	43.8±6.7^{a}	33.4±2.9^{a}	43.8±1.8^{a}	37.3±8.8^{a}	35.5±1.7^{a}	39.5±4.2^{ab}	38.9±5.9^{b}
RTfs	44.8±9.4^{a}	32.4±0.2^{ab}	44.7±3.3^{a}	42.7±8.2^{a}	36.5±2.6^{a}	41.0±2.8^{ab}	40.4±6.6^{a}
Thousand grain weight (g)							
CT	38.0±0.3^{b}	32.7±0.9^{b}	37.2±1.9^{a}	37.9±0.1^{a}	34.1±0.4^{a}	36.7±0.9^{a}	36.1±2.2^{bc}
SM	39.0±1.3^{ab}	31.1±0.7^{b}	37.5±2.2^{a}	38.1±0.8^{a}	34.2±0.9^{a}	36.6±2.7^{a}	36.1±3.1^{bc}
FM	39.0±0.7^{ab}	29.3±0.8^{c}	37.2±2.3^{a}	38.3±0.4^{a}	33.7±2.7^{a}	36.0±1.2^{a}	35.6±3.7^{c}
RT	39.6±0.8^{ab}	31.2±0.6^{b}	38.8±1.1^{a}	38.5±1.1^{a}	33.6±1.2^{a}	37.2±2.1^{a}	36.5±3.3^{abc}
RTf	39.4±0.4^{ab}	34.8±0.9^{a}	38.7±2.0^{a}	38.2±0.6^{a}	35.0±0.4^{a}	38.0±0.6^{a}	37.4±2.0^{a}
RTfs	39.8±1.4^{a}	31.9±1.5^{b}	38.7±1.2^{a}	38.4±0.2^{a}	33.0±0.5^{a}	38.3±0.6^{a}	36.7±3.2^{ab}

Nitrogen application rates are N0 (0 kg N ha^{-1}) and N180 (180 kg N ha^{-1}). Tillage treatments include conventional tillage (CT, as control), stalk mulching (SM), film mulching (FM), ridge tillage without mulch (RT), ridge tillage with film on ridges (RTf), and ridge tillage with film on ridges and stalk in furrows (RTfs). Values are mean ± SD (n = 3). Grand mean is the value averaged across growing seasons and N treatments (n = 18). Means with same letters in the same column are not significantly different (P > .05). Grey background color indicates significant difference between the tillage treatment and CT (P < .05). Averaged across N and tillage treatments, spike number per hectare was 2.99 ± 0.97^{a}, 1.94 ± 0.66^{b}, and 3.11 ± 1.09^{a} million spikes ha^{-1}, grain number per spike was 41.6 ± 7.9^{a}, 33.4 ± 2.9^{a}, and 41.7 ± 3.8^{a} grains spike^{-1}, thousand grain weight was 38.7 ± 0.9^{a}, 32.9 ± 1.9^{b}, and 37.6 ± 1.7^{a} g in 2011–2012, 2012–2013, and 2013–2014 growing season, respectively. Averaged across growing seasons and tillage treatments, spike number per hectare was 1.87 ± 0.43^{b} and 3.49 ± 0.86^{a} million spikes ha^{-1}, grain number per spike was 39.6 ± 7.6^{a} and 38.1 ± 5.3^{a} grains spike^{-1}, thousand grain weight was 36.3 ± 3.6^{a} and 36.4 ± 2.2^{a} g in N0 and N180 treatment, respectively.

the soil water content in the dry growing season 2012–2013 greatly increased due to heavy rainfall with a total of 116.2 mm (Fig. 1) at the maturity stage. The heavy rainfall event at maturity did not affect the calculation of evapotranspiration (Eq. 2) as wheat was harvested just after the rainfall, and thus the evaporation was negligible and increment of soil water storage was equal to the rainfall amount.

Results of canopy moisture (Fig. 4) showed that mass-based canopy moisture gradually decreased from regreening (stage 6 in Feekes scale, late Feb–early Mar) to maturity (late May–early Jun), while area-based canopy moisture gradually increased from regreening to grain-filling stage (middle May), and dramatically decreased at maturity. Ridge tillage and mulching tended to increase mass-based and area-based canopy moisture compared with CT. For example, in N180 treatments during Feb 25th–Mar 31st, 2012, mass-based canopy moisture (Fig. 4d) was 307.6%–337.5% in CT, while it was 355.2%–406.2% in SM, 369.3%–472.0% in FM, 377.4%–450.1% in RT, 385.2%–454.6% in RTf,

Table 4
Effects of growing season, tillage, and N treatments on evapotranspiration (mm) and water use efficiency (kg ha^{-1} mm^{-1}).

	N0			N180			Grand mean
	2011–2012	2012–2013	2013–2014	2011–2012	2012–2013	2013–2014	
Evapotranspiration (mm)							
CT	360±29^{a}	267±19^{a}	318±10^{a}	417±20^{a}	272±19^{a}	300±51^{a}	322±9^{a}
SM	301±31^{bc}	215±8^{c}	261±29^{bc}	398±28^{a}	255±12^{ab}	285±53^{a}	286±64^{c}
FM	285±18^{c}	217±11^{c}	251±17^{c}	383±23^{a}	218±17^{c}	266±54^{a}	270±62^{d}
RT	311±25^{bc}	251±26^{ab}	233±32^{c}	379±21^{a}	256±21^{ab}	297±51^{a}	288±57^{bc}
RTf	346±22^{ab}	246±9a^{bc}	260±19^{bc}	397±19^{a}	259±11^{a}	266±59^{a}	296± 62^{b}
RTfs	292±25^{c}	224±25^{bc}	300±31^{ab}	386±31^{a}	227±22^{bc}	297±48^{a}	288±62^{bc}
Water use efficiency (kg ha^{-1} mm^{-1})							
CT	9.3±1.4^{b}	4.4±0.2^{c}	11.6±0.5^{c}	13.1±2.2^{a}	10.1±0.5^{c}	19.8±1.9^{a}	11.4±4.9^{c}
SM	10.5±1.1^{b}	6.6±0.7^{a}	15.8±0.8^{ab}	15.6±1.3^{a}	12.1±0.5^{bc}	23.5±5.6^{a}	14.0±5.8^{b}
FM	14.3±1.9^{a}	6.8±0.2^{a}	16.6±1.6^{a}	15.8±1.6^{a}	14.5±1.8^{ab}	25.9±3.2^{a}	15.6±6.0^{a}
RT	11.8±1.5^{ab}	5.1±0.8^{bc}	16.7±2.2^{a}	15.1±2.5^{a}	11.7±1.3^{c}	19.6±2.0^{a}	13.3±5.0^{b}
RTf	10.6±0.5^{b}	5.9±0.7^{ab}	15.3±2.2^{ab}	14.5±1.8^{a}	12.1±0.2^{c}	23.0±4.1^{a}	13.6±5.6^{b}
RTfs	12.1±3.0^{ab}	7.0±1.1^{a}	13.1±2.1^{bc}	15.9±0.8^{a}	14.8±2.2^{a}	22.4±3.9^{a}	14.2±5.2^{b}

Nitrogen application rates are N0 (0 kg N ha^{-1}) and N180 (180 kg N ha^{-1}). Tillage treatments include conventional tillage (CT, as control), stalk mulching (SM), film mulching (FM), ridge tillage without mulch (RT), ridge tillage with film on ridges (RTf), and ridge tillage with film on ridges and stalk in furrows (RTfs). Values are mean ± SD (n = 3). Grand mean is the value averaged across growing seasons and N treatments (n = 18). Means with same letters in the same column are not significantly different (P > .05). Grey background color indicates significant difference between the tillage treatment and CT (P < .05). Averaged across N and tillage treatments, evapotranspiration was 354.5 ± 49.2^{a}, 242.1 ± 24.8^{b}, and 277.8 ± 41.9^{b} mm, while water use efficiency was 13.2 ± 2.7^{b}, 9.2 ± 3.7^{c}, and 18.6 ± 4.9^{a} kg ha^{-1} mm^{-1} in 2011–2012, 2012–2013, and 2013–2014 growing season, respectively. Averaged across growing seasons and tillage treatments, evapotranspiration was 274.3 ± 45.9^{b} and 308.6 ± 70.3^{a} mm, while water use efficiency was 10.7 ± 4.2^{b} and 16.6 ± 5.0^{a} kg ha^{-1} mm^{-1} in N0 and N180 treatment, respectively.

and 426.7%–507.8% in RTfs; in N180 treatments during regreening to maturity in 2012, average area-based canopy moisture (Fig. 4m) was 1.099 mm in CT, and it was 1.233 mm in SM, 1.365 mm in FM, 1.213 mm in RT, 1.246 mm in RTf, and 1.400 mm in RTfs. Film mulching (FM) resulted in greater mass-based and area-based canopy moisture compared with stalk mulching (SM). Compared with RT, mulched ridge tillage systems (RTf and RTfs) tended to increase mass-based and area-based canopy moisture. Additionally, mass-based canopy moisture during regreening to grain-filling was positively correlated with grain yield, but mass-based canopy moisture at maturity was negatively correlated with grain yield; while area-based canopy moisture during regreening to maturity was positively correlated with grain yield.

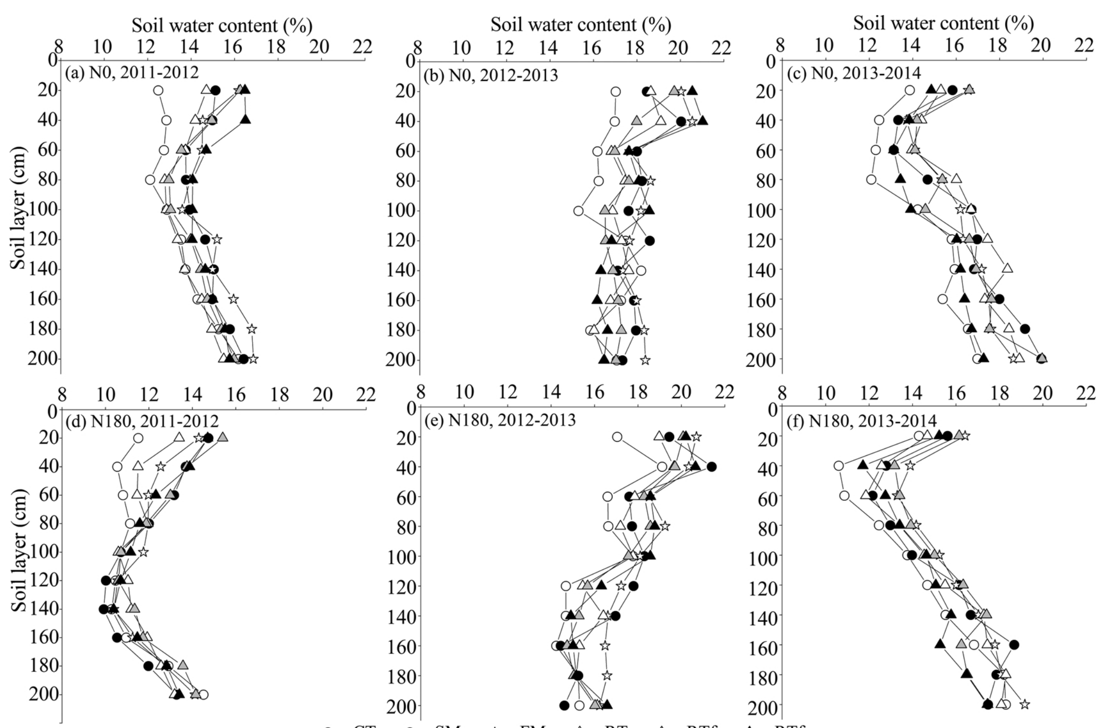

Fig. 3. Soil water content (0–200 cm depth, mass-based) at the phase of maturity of wheat. Nitrogen application rates are N0 (0 kg N ha^{-1}) and N180 (180 kg N ha^{-1}). Tillage treatments include conventional tillage (CT, as control), stalk mulching (SM), film mulching (FM), ridge tillage without mulch (RT), ridge tillage with film on ridges (RTf), and ridge tillage with film on ridges and stalk in furrows (RTfs).

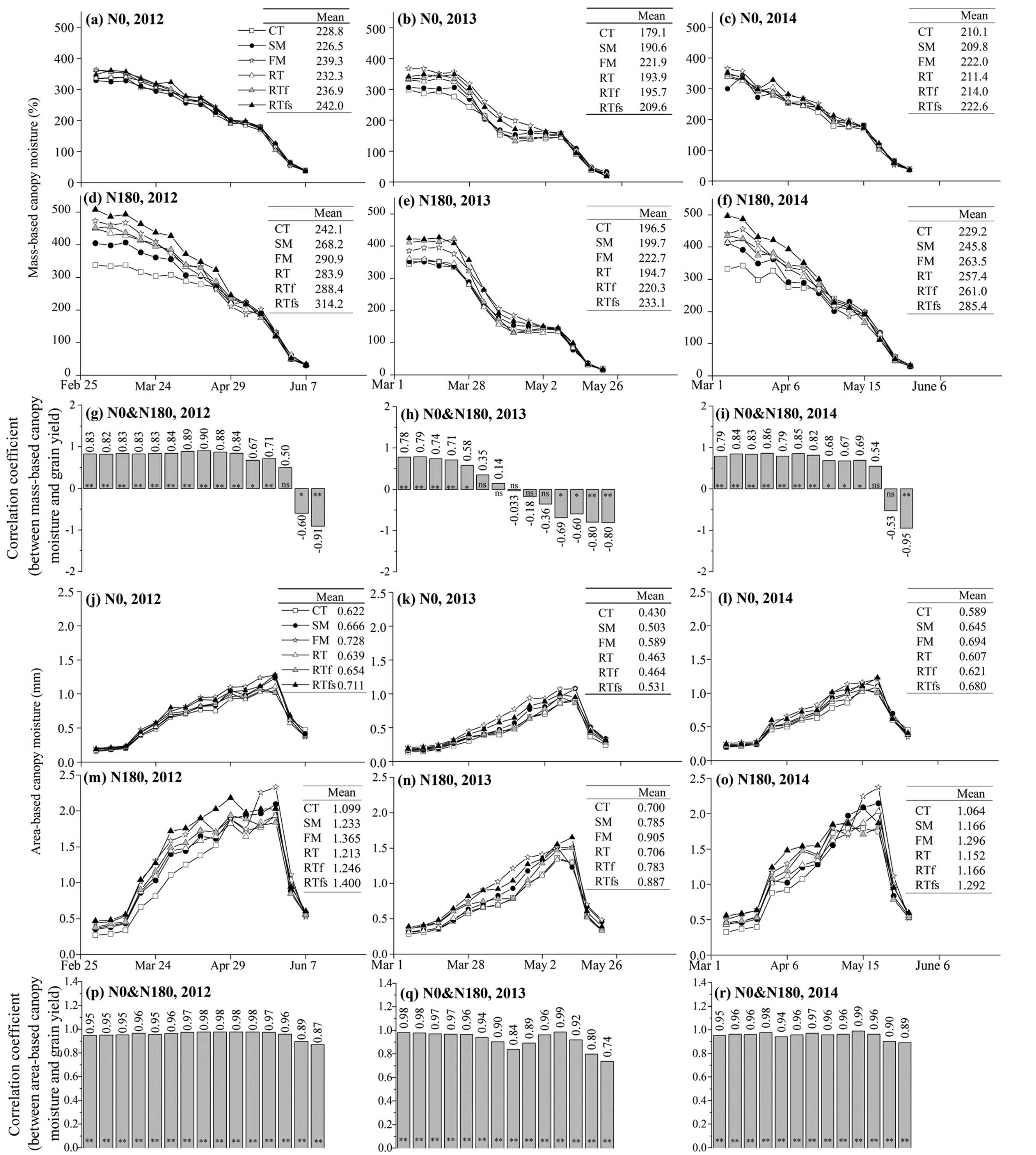

Fig. 4. Variations of canopy moisture (% (mass-based) and mm (area-based), $n = 6$) and correlation coefficients ($n = 12$) between canopy moisture at different sampling date and grain yield at maturity. Ranges of sampling date are: Feb 25th–Jun 7th, 2012 (103 d), Mar 1st–May 26th, 2013 (87 d), and Mar 1st–Jun 6th, 2014 (98 d). Nitrogen application rates are N0 (0 kg N ha^{-1}) and N180 (180 kg N ha^{-1}). Tillage treatments include conventional tillage (CT, as control), stalk mulching (SM), film mulching (FM), ridge tillage without mulch (RT), ridge tillage with film on ridges (RTf), and ridge tillage with film on ridges and stalk in furrows (RTfs). Mean is the value averaged across sampling dates. ns $P > .05$; * $P < .05$; ** $P < .01$.

3.5. Leaf area index and total chlorophyll in flag leaf

Results of leaf area index (*LAI*, Table 5) showed that ridge tillage and mulching tended to decrease *LAI*. Evenly, averaged across growing seasons and N treatments (grand mean), ridge tillage and mulching treatments decreased *LAI* by 3.1%–10.4% compared with CT. Ridge tillage and mulching tended to increase total chlorophyll in flag leaf (*TChl*) compared with CT. Evenly, averaged across growing seasons and N treatments (grand mean), ridge tillage and mulching (except for RT) increased *TChl* by 8.3%–22.8% compared with CT. Finally, a response surface analysis was conducted to investigate the effects of *LAI* and *TChl* on grain yield, and the results (Fig. 5) showed that grain yield increased with *LAI* and *TChl*.

Table 5
Effects of growing season, tillage, and N treatments on leaf area index and total chlorophyll in flag leaf (mg g^{-1} DW).

	N0			N180			Grand mean
	2011–2012	2012–2013	2013–2014	2011–2012	2012–2013	2013–2014	
Leaf area index							
CT	1.17±0.05^{a}	0.72±0.04^{a}	1.33±0.17^{a}	2.61±0.20^{a}	1.36±0.01^{a}	2.59±0.25^{ab}	1.63±0.75^{a}
SM	0.98±0.07^{cd}	0.61±0.04^{cd}	0.99±0.05^{b}	2.56±0.01^{ab}	1.36±0.03^{a}	2.91±0.17^{a}	1.57±0.88^{b}
FM	1.09±0.04^{ab}	0.69±0.05^{abc}	1.10±0.10^{b}	2.43±0.04^{ab}	1.31±0.06^{ab}	2.38±0.12^{b}	1.50±0.69^{c}
RT	1.06±0.04^{bc}	0.71±0.09^{ab}	1.06±0.12^{b}	2.36±0.16^{b}	1.22±0.07^{b}	2.43±0.31^{b}	1.47±0.70^{c}
RTf	1.07±0.03^{bc}	0.62±0.05^{bcd}	1.08±0.04^{b}	2.61±0.07^{a}	1.34±0.07^{a}	2.76±0.19^{ab}	1.58±0.84^{ab}
RTfs	0.91±0.07^{d}	0.58±0.04^{d}	0.97±0.16^{b}	2.46±0.04^{ab}	1.34±0.05^{a}	2.49±0.18^{b}	1.46±0.78^{c}
Total chlorophyll in flag leaf (mg g^{-1} DW)							
CT	8.41±0.84^{a}	3.25±0.07^{d}	3.96±0.44^{c}	8.84±0.96^{cd}	5.36±0.16^{d}	6.94±0.07^{c}	6.13±2.23^{d}
SM	5.19±0.58^{d}	4.52±0.10^{b}	6.82±0.63^{a}	9.76±0.27^{b}	5.92±0.20^{bc}	7.62±0.87^{c}	6.64±1.83^{c}
FM	7.37±0.29^{bc}	3.96±0.01^{bc}	5.97±0.25^{b}	10.90±0.23^{a}	5.78±0.62^{cd}	9.97±0.25^{a}	7.32±2.51^{a}
RT	4.70±0.14^{d}	3.42±0.43^{cd}	3.87±0.11^{c}	8.22±0.16^{de}	6.43±0.25^{b}	7.64±0.12^{c}	5.71±1.90^{e}
RTf	6.76±0.32^{c}	3.89±0.46^{c}	5.93±0.27^{b}	9.24±0.22^{bc}	6.41±0.07^{b}	9.04±0.26^{b}	6.88±1.91^{b}
RTfs	7.86±0.33^{ab}	5.50±0.47^{a}	7.27±0.36^{a}	7.80±0.12^{e}	7.62±0.19^{a}	9.14±0.30^{b}	7.53±1.14^{a}

Nitrogen application rates are N0 (0 kg N ha^{-1}) and N180 (180 kg N ha^{-1}). Tillage treatments include conventional tillage (CT, as control), stalk mulching (SM), film mulching (FM), ridge tillage without mulch (RT), ridge tillage with film on ridges (RTf), and ridge tillage with film on ridges and stalk in furrows (RTfs). Values are mean ± SD (n = 3). Grand mean is the value averaged across growing seasons and N treatments (n = 18). Means with same letters in the same column are not significantly different (P > .05). Grey background color indicates significant difference between the tillage treatment and CT (P < .05).

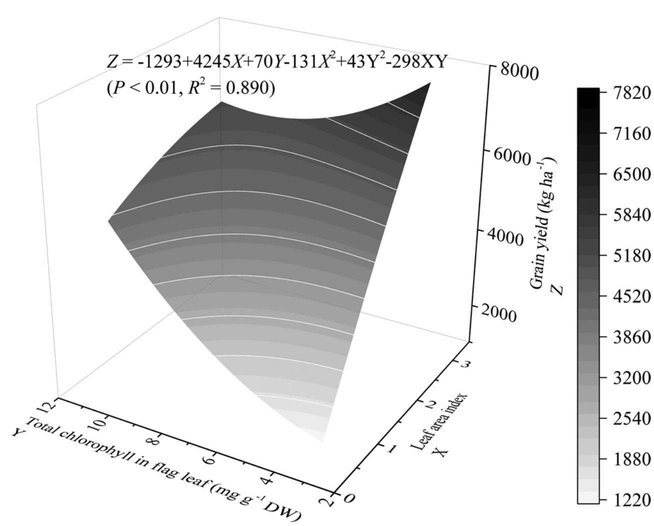

Fig. 5. Response surface of grain yield to leaf area index and total chlorophyll in flag leaf (n = 36).

4. Discussion

Soil water content and crop traits are sensitive to climatic conditions such as rainfall, tillage practices and fertilizer management (Liu and Siddique, 2015; Yang et al., 2015). Our findings (Table 1) confirmed that soil water content and crop traits had significant responses to season, tillage, N, and their interactions. Therefore, it is possible to improve wheat productivity by adjusting tillage practices and N fertilization under variable rainfall.

4.1. Responses of grain yield and yield components

Wheat productivity is highly dependent on N supply and water availability which is affected by tillage practices (Seddaiu et al., 2016). Results presented above (Table 2) showed that ridge tillage and mulching increased the grand mean of grain yield by 4.2%–15.2% compared with conventional tillage (CT). Sime et al. (2015) and Wang et al. (2016) reported that film mulching had even greater effect on grain yield of maize, i.e., film mulching increased grain yield of maize by 23%–107%. Higher grain yields obtained under ridge tillage and mulching treatments partly result from higher moisture in soil layers and crop canopy (Zheng et al., 2014). Besides, high soil temperature in ridge tillage and film mulching treatments enhances mineralization of organic matter and supply of soil nutrients, and thus is also responsible for higher grain yield (Wang et al., 2016; Yang et al., 2015; Zheng et al., 2014). Mulching with film or stalk further increased grain yield in ridge tillage system (Table 2). Similarly, Zhang et al. (2011) reported RTfs was an efficient ridge tillage system for crop production in the Loess Plateau of China. Besides, we found that effects of ridge tillage and mulching on grain yield were affected by rainfall. Ridge tillage and mulching most likely increased grain yield more when water supply was limited in the dry growing season 2012–2013 (Table 2). Wang et al. (2016) also observed that film mulching most likely increased the crop yield more when water availability was a limiting factor.

It is essential to identify the key components which limit wheat yield to achieve high grain yields (Lu et al., 2016). Ridge tillage and mulching had a positive effect on yield components, while yield components were also affected by N treatments and growing seasons (Table 3). Liu and Siddique (2015) also found that ridge tillage and film mulching increased grain number per spike (*GNPS*) and thousand grain weight (*TGW*) of maize. A multiple regression analysis showed that *SNPH* and *GNPS* had significant contribution to grain yield under current conditions when all the three yield components were considered. Lu et al. (2016) also observed that greater wheat yield was highly attributed to greater *SNPH*, resulted from elevated pre-winter stem numbers and greater percentage of productive stems.

4.2. Responses of water availability and water use efficiency

In rain-fed regions, it is important to reduce evapotranspiration so as to improve water availability (Liu et al., 2016). The current study showed that limited water supply in the dry season significantly decreased evapotranspiration, while N application significantly increased evapotranspiration (Table 4). Ridge tillage and mulching are accepted as effective measures for reducing evapotranspiration (Diaz-Hernandez and Salmeron, 2012; Liu and Siddique, 2015; Wang et al., 2014). Liu and Siddique (2015) reported that evapotranspiration in RTf (142.8 mm) was lower than that in CT (216.7 mm), partly due to the film mulching. We found (Table 4) that ridge tillage and mulching tended to decrease evapotranspiration, while evapotranspiration was also affected by N fertilization and rainfall. For example, ridge tillage and mulching decreased evapotranspiration compared with CT, especially when N was deficient (N0). Liu et al. (2014) also reported that N fertilization tended to increase evapotranspiration in ridge tillage and mulching treatments. Additionally, we found (Table 4) that when fertilized with N (N180), ridge tillage and mulching tended to reduce evapotranspiration in the dry growing season 2012–2013 rather than in humid growing seasons 2011–2012 and 2013–2014. Similarly, Diaz-Hernandez and Salmeron (2012) found that film mulching had marginal effects on evapotranspiration and soil water content during the humid growing season. Some explanations are that in wet period, (i) evapotranspiration is relatively low while film mulching has no significant influence on soil water recharge; (ii) compared with transpiration, evaporation which was affected by film mulching contributes less to evapotranspiration.

Soil water availability can be improved by reducing evapotranspiration. Our findings showed that as ridge tillage and mulching decreased evapotranspiration (Table 4), water availability in 0–80 cm soil layers was improved in all growing seasons and N treatments (Fig. 3). Liu et al. (2013) and Liu and Siddique (2015) also observed that ridge tillage and mulching improved water availability in soil profiles. One explanation is that ridge tillage has high efficiency in harvesting rainwater, while, in addition, mulching effectively reduces evaporation (Liu and Siddique, 2015; Wang et al., 2014). Additionally, ridge tillage and mulching have positive effects on aggregation processes and thus enhance water holding capacity, which then further improve water availability in soil layers (Liu et al., 2013).

Plant water status will benefit from greater soil water content. Canopy moisture is a direct parameter reflecting plant water status, which is closely related to crop growth and grain yield (Durigon and de Jong van Lier, 2013; Winterhalter et al., 2011). Drought-induced decreases in canopy moisture negatively affect crop physiological traits such as photosynthesis, and thus reduce crop yields (Yan et al., 2012). Our findings showed (Fig. 4) that ridge tillage and mulching tended to increase canopy moisture compared with CT, partly due to greater soil water content in the 0–80 cm profiles (Fig. 3). Additionally, we found (Fig. 4) that film was a better mulching material than stalk in terms of improving canopy moisture; while mulching with film or stalk further increased canopy moisture in ridge tillage system. The relationship between grain yield and mass-based canopy moisture was complex. On one hand, grain yield was positively correlated with mass-based canopy moisture during regreening (stage 6 in Feekes scale, late Feb–early Mar) to grain-filling stage (middle May, Fig. 4). Therefore, in ridge tillage and mulching treatments, the greater mass-based canopy moisture during regreening to grain-filling stage was beneficial for grain yield. On the other hand, grain yield was negatively correlated with mass-based canopy moisture at maturity (late May–early Jun, Fig. 4). One explanation is that mass-based canopy moisture at maturity reflected the mean moisture of grain and straw. Moisture in grain (14%–17%) was lower than that in straw (averaged 30%–35%) (detailed data not shown), and thus greater mass-based canopy moisture at maturity indicated lower proportion of grain in the above-ground biomass. In contrast, the relationship between grain yield and area-based canopy moisture was simple, i.e., consistently positive relationship. The explanation is that area-based canopy moisture largely reflects the population size, and greater area-based canopy moisture is associated with greater biomass and grain yield.

Water use efficiency (*WUE*) has responses to factors which affect grain yield and evapotranspiration (Liu and Siddique, 2015). We found (Table 4) that limited water supply in the dry growing season tended to decrease *WUE*, partly due to the lower grain yield; N application significantly increased *WUE*, partly due to the greater grain yield; while ridge tillage and mulching tended to increase *WUE*, partly due to the greater grain yield and lower evapotranspiration. Similarly, Liu et al. (2016) found that FM increased *WUE* of maize, while Liu and Siddique (2015) observed that RTf and RT significantly increased *WUE* of potato. Additionally, crops tend to transpire more water rather than loss through evaporation in ridge tillage and mulching treatments than in CT, which is also responsible for higher *WUE* (Wang et al., 2014). Besides, Table 4 shows that ridge tillage and mulching tended to increase *WUE* especially when supplied with deficient N (N0).

4.3. Responses of leaf area index and chlorophyll concentration

Leaf area index (*LAI*) is closely related to crop productivity, and higher water availability usually leads to greater *LAI* (Li et al., 2015; Liu et al., 2016; Salvagiotti and Miralles, 2008). We found that in ridge tillage and mulching treatments, although water availability was improved (Fig. 3, 4), *LAI* was reduced (Table 5). One explanation is that row spacing in FM and ridge tillage systems (30 cm) was larger than that in CT (20 cm) (Fig. 2) while wheat was planted at the same rate. Hence, plant density in each planting row was greater in FM and ridge tillage systems than in CT, what inhibited *LAI* values. Additionally, lower *LAI* in SM partly resulted from its lower soil temperature compared with CT: previous studies showed that soil temperature was 0.9 °C lower in SM than in CT in rain-fed wheat fields (Yang et al., 2015); similarly, Ram et al. (2012) reported that SM reduced soil temperature by 3 °C compared with CT in irrigated maize-wheat fields. Besides, we found (Table 5) that ridge tillage and mulching decreased *LAI* especially when N supply was deficient (N0). Li et al. (2015) also reported that N fertilization and mulching had positive interaction on *LAI*.

Leaf chlorophyll concentration is closely related to crop productivity, and higher water availability usually results in greater chlorophyll concentration (Shefazadeh et al., 2012). We found (Table 5) that ridge tillage and mulching (except for RT) increased total chlorophyll in flag leaf (*TChl*) compared with CT, partly due to the greater soil water content and canopy moisture (Figs. 3 and 4). Shefazadeh et al. (2012) also reported that chlorophyll concentration in wheat leaves was highly correlated with crop water status.

A response surface analysis showed (Fig. 5) that grain yield increased with both *LAI* and *TChl*. Similarly, previous studies showed that crop yield was positively related to *LAI* and *TChl* (Li et al., 2015; Salvagiotti and Miralles, 2008; Shefazadeh et al., 2012). We concluded that lower *LAI* in ridge tillage and mulching treatments resulted in grain yield loss, but the loss was alleviated by greater *TChl*.

5. Conclusions

The effects of ridge tillage and mulching on water availability, grain yield, and water use efficiency (*WUE*) in rain-fed winter wheat varied with rainfall and N conditions. Ridge tillage and mulching tended to decrease evapotranspiration, and increase grain yield and *WUE* compared with conventional tillage (CT), especially when rainfall and N were deficient. Ridge tillage and mulching increased moisture in upper soil layers (0–80 cm). Mass-based canopy moisture during regreening to grain-filling stage was positively correlated with grain yield. Area-based canopy moisture during regreening to maturity was positively correlated with grain yield. Film was a better mulching material than stalk in terms of improving canopy moisture. Ridge tillage and mulching had positive interactions on canopy moisture and grain yield. Spike number per hectare and grain number per spike made significant contributions to grain yield when all three yield components were considered. Grain yield increased with leaf area index (*LAI*) and total chlorophyll in flag leaves (*TChl*). In ridge tillage and mulching treatments, lower *LAI* led to grain yield loss, but the loss was alleviated by greater *TChl*. Overall, ridge tillage and mulching improved water availability, grain yield, and *WUE* in rain-fed winter wheat, especially when N and rainfall were deficient.

Acknowledgements

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