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Maize Yield Response to Nitrogen Rate and Plant Density under Film Mulching

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ABSTRACT

Film mulching has significantly improved crop productivity in semiarid areas. We hypothesized that plants grown under the film-mulched system (FM) require higher N rates and higher plant densities than the non-mulched system (NM) to optimize grain yield and water use efficiency (WUE). A 2-yr field experiment was conducted at the Changwu experimental station to evaluate the effects of N supply and plant density on grain yield, yield components, evapotranspiration, and WUE in spring maize (*Zea mays* L.) with and without film mulching. Results showed that FM improved topsoil water content. Mulch practice × N rate and mulch practice × plant density interactions existed for yield and WUE in both years. Regression analysis showed that yield and WUE increased with increasing N rate and plant density for FM. The predicted maximum yield (14.3 and 15.1 Mg ha^{-1} in 2013 and 2014, respectively) and WUE (31.3 and 38.4 kg ha^{-1} mm^{-1} in 2013 and 2014, respectively) for FM were obtained at 280 kg N ha^{-1} and 80,000 plants ha^{-1}. Lower N amounts and lower plant densities were required for NM to obtain the maximum yield and WUE. However, field experiments showed that the N amount of 225 kg ha^{-1} in FM increased N use efficiency while yielding >94% of the maximum. In conclusion, film mulching together with optimum N application rates and plant densities can improve maize production and WUE in semiarid regions.

Core Ideas

- Film mulching significantly improved soil moisture.
- Film mulching required a higher N rate and plant density for maximum maize productivity.
- Optimum management can improve maize production and water use in semiarid regions.

Water stress is the main factor limiting crop production in dryland areas of the world (Zand-Parsa et al., 2006; Li et al., 2009). On the Loess Plateau in northwest China, more than 80% of arable land is dominated by rain-fed cropping systems (Huang et al., 2011). Low crop production in this region is closely associated with limited and unevenly distributed precipitation, low water availability, and high evaporation (Zhou et al., 2009). This issue has become increasingly serious due to climate change, which significantly threatens agricultural sustainability in rain-fed arid and semiarid areas (Pan et al., 2011; Tao and Zhang 2011). Therefore, increasing water use efficiency (WUE) through highly effective utilization of precipitation is a key priority to improve agricultural production and maintain food security in the Loess Plateau region.

The film mulching technique has proven to be an effective measure to improve grain yield and WUE in semiarid and arid farming areas (Jia et al., 2006; Ramakrishna et al., 2006; Zhao et al., 2012). Recently, a novel technique using double ridges and furrows mulched with plastic film was found to be more efficient for improving grain yield and WUE in spring maize compared with the conventional practices (Zhou et al., 2009; Ye and Liu, 2012; Liu et al., 2014a). This new planting pattern contributed to better soil water conditions and higher topsoil temperature, especially during seedling development; it increased seed fertility and in turn resulted in the final yield increase (Zhou et al., 2009). This technique has been widely applied in dryland farming systems, particularly in areas characterized by lack of irrigation and low spring temperatures (Zhang et al., 2005; Liu et al., 2009). However, irrational N application regimes (Liu et al., 2014b; Li et al., 2015) and low plant densities (Liu et al., 2014a) are the key factors limiting the further improvement of crop yield and resource use efficiency in this mulching system.

N fertilizer plays a significant role in improving grain yield and WUE (Hernández et al., 2015; Li et al., 2015). Previous research focusing on contrasts in water availability (i.e., rain-fed

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Abbreviations: EN, ear number per square meter; ET, evapotranspiration; FM, ridge-furrow mulched with plastic film; KN, kernel numbers per ear; KW, 1000-kernel weight; NM, ridge-furrow with no mulching; WUE, water use efficiency.

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vs. irrigated) showed that the response of grain yield and WUE to N supply is dependent to a great extent on the amount of available water during the growing season (Gonzalez-Dugo et al., 2010; Hernández et al., 2015). Given that film mulching improved water availability (Zhou et al., 2009), the response of grain yield and WUE to N supply may be different under film-mulched and non-mulched growing conditions. A recent study found that grain yield and WUE increased closely with N rate up to 90 kg ha^{-1} in both film-mulched and non-mulched treatments, the former being 52 and 48% higher, respectively, than the latter; however, the yield of film-mulched maize (~7.5 Mg ha^{-1}) remained low (Li et al., 2015). High yields of 14.0 Mg ha^{-1} have been obtained when maize was grown with film mulching combined with successful N application (Bu et al., 2013). Presently, knowledge about the optimum levels of N for high-yielding maize under film mulched conditions is scarce, highlighting the need to investigate how grain yield and WUE in high-yielding maize respond to N supply under film mulching in dryland areas.

Plant density is another factor that plays an important role in grain yield (Cox, 1996; Tokatlidis and Koutroubas, 2004). Similar to N rate, the optimum plant density is affected by moisture conditions (Sangoi et al., 2002; Kiniry et al., 2002). The optimum plant density for maize hybrids grown under drought-prone conditions (e.g., 35,900 to 46,600 plants ha^{-1} in a dry year) was much lower than for maize grown under favorable moisture conditions (e.g., 57,900 to 78,600 plants ha^{-1} in a wet year) (Tokatlidis et al., 2011). Plant density of spring maize is usually <50,000 plants ha^{-1} in smallholder fields in the northwest Loess Plateau (Chen et al., 2009). However, simulations through the Hybrid-Maize model indicated that the optimum plant density varied from 65,000 to 85,000 plants ha^{-1} for film-mulched maize in this region (Bu, 2013), although there is a lack of field experiments. Therefore, it is urgent to verify the applicability of the optimum plant density for high-yielding maize under film mulching in dryland fields.

We hypothesized that the novel film-mulched tillage required higher N rates and higher plant densities for optimizing grain yield and WUE compared with non-mulched tillage. To test this hypothesis, a 2-yr field study was conducted to evaluate the effects of N rates and plant densities on maize grain yield, yield components, dynamics and balance of soil water, evapotranspiration (ET), and WUE under film-mulched and non-mulched conditions. Results from this study will be helpful for optimizing agricultural management practices in terms of both maize production and WUE in rain-fed arid and semiarid areas.

MATERIALS AND METHODS

Site Description

Field research during the 2013 and 2014 growing seasons was conducted at the Changwu Research Station of Agriculture and Ecology on the Loess Plateau of China (35.28° N, 107.88° E; ~1200 m elevation). The station is located in a region with a typical semiarid climate, with a mean annual temperature of 10.1°C and precipitation of 556 mm (1993–2012). Approximately 73% of the precipitation occurs during the maize growing season (May–September). Rain-fed cropping systems in which maize or wheat (*Triticum aestivum* L.) is grown as a continuous monocrop are predominant at the study site. The soil is classified as Cumuli-Ustic Isohumosols (sand, 4%; silt, 59%; clay, 37%) according to the Chinese Soil Taxonomy (Gong et al., 2007). The chemical properties of the soil (0–20 cm) before planting in 2013 were as follows: pH of 8.4, bulk density of 1.3 g cm^{-3}, organic matter of 13.92 g kg^{-1}, total N of 0.97 g kg^{-1}, Olsen-P of 10.95 mg kg^{-1}, mineral N of 12.93 mg kg^{-1}, field capacity of 22.4% by weight (g g^{-1}), and a wilting point at 9% by weight (g g^{-1}).

Experimental Design and Treatments

The study was arranged as a randomized complete block design with three replications. The plot size was 30 m^2 (5 m by 6 m) each. Before planting, all plots were laid out with ridge-furrow; that is, there were alternating large (60 cm) and small (40 cm) ridges with ridge heights of 10 and 15 cm, respectively. Adjacent ridges were separated by furrows, in which the maize seeds were planted. The three treatment factors were mulch practice, N application rate, and plant density. A total of 24 treatments were examined.

Two mulch practices were established each year: (i) ridge-furrow mulched with plastic film (FM), which has been widely adopted in the semiarid areas of northwest China (Eldoma et al., 2016); and (ii) ridge-furrow with no mulching (NM, control). In FM, both ridges and furrows were mulched with pieces of transparent plastic film of 120 to 130 cm wide before planting. The midline of the large ridge was the joint between the two pieces of film where the soil was placed on top of the film. The plastic film was used throughout the entire maize growing season. It was removed at harvest and the field was re-mulched before seeding in the second year.

Four different N application rates were used in 2013: 0, 170, 200, and 230 kg N ha^{-1} (hereafter referred to as N0, N170, N200, and N230, respectively). Due to the fact that the N levels applied in 2013 did not fully meet the N demand for film-mulching maize in the high-density treatment, we adjusted the four different N rates (to be used in 2014) to 0, 170, 225, and 280 kg N ha^{-1} (N0, N170, N225, and N280, respectively). In both years, planting rates were 50,000, 65,000, and 80,000 plants ha^{-1}, denoted PD1, PD2, and PD3, respectively, for the low, medium, and high plant density treatments. The three density levels were selected based on the common practice of local farmers (~50,000 plants ha^{-1}) and the simulation results of the Hybrid-Maize model (optimal range of 65,000 to 80,000 plants ha^{-1}; Bu, 2013).

All N fertilizer was applied as urea (N 46%) three times: 40% was applied before planting as a basal N fertilizer, the remainder was applied at the jointing stage (30%) and at the silking stage (30%) as a topdressing using a hole-sowing machine. After ridging the treatment plots, the base fertilizer consisted of basal N fertilizer, 40 kg P ha^{-1} (calcium superphosphate, P_2O_5 12%) and 80 kg K ha^{-1} (potassium sulfate, K_2O 45%), which was manually spread over the soil surface and then plowed into the subsurface before planting each plot. All other agronomic practices were standard and uniform for all the treatments. There was no irrigation during the maize-growing season, and natural rainfall was the only water resource for maize growth. Monthly weather data was provided by the Changwu meteorological monitoring station situated at approximately 50 m from the experimental field.

Table 1. Total precipitation, mean air temperature and total reference evapotranspiration in the period from 1993 to 2012 (20-yr average) and for the months of May to September in 2013 and 2014.

Month	Total precipitation			Mean air temperature			Total reference evapotranspiration		
	20-yr avg.	2013	2014	20-yr avg.	2013	2014	20-yr avg.	2013	2014
	mm			°C			mm		
May	46	66	29	16	17	15	161	146	152
June	62	42	56	21	21	20	196	157	140
July	103	237	22	23	22	23	151	110	177
August	91	38	136	21	23	20	118	147	123
September	89	117	188	16	16	15	84	75	66

Maize was cropped (2012 season) without fertilization in the study site preceding our experiment. The high-yielding maize hybrid 'Pioneer 335' (of ~1510 growing degree-days) was planted using a hand-powered hole-drilling machine on 23 Apr. 2013 and 28 Apr. 2014. The plots were harvested at ripeness from 18 to 23 Sept. 2013 and from 20 to 26 Sept. 2014.

Sampling and Analysis

At harvest, 8 m^2 (4 rows each 2 m long) in the center of each plot were manually harvested to determine grain yield (on a 15.5% moisture basis, Mg ha^{-1}) and yield components (ear number per square meter, kernel number per ear, and 1000-kernel weight).

Soil samples were collected 1 to 2 d before planting and at physiological maturity. Core samples were taken from each plot at 20-cm depth intervals down to 200 cm. The samples were oven-dried at 105°C to a constant weight to determine soil gravimetric water content (gravimetric soil moisture, kg kg^{-1}).

The reference evapotranspiration was estimated using the FAO Penman–Monteith equation (Allen et al., 1998) to assess the evaporative demand of the atmosphere. The ET was calculated as follows (Liu et al., 2014a): ET = DW + P, where DW is the change in soil water over the growing season (i.e., water storage at planting minus water storage at harvest at 200-cm depth) and P is the precipitation (mm) during the growing season. The WUE was calculated as grain yield (kg ha^{-1}) divided by ET (mm).

Data Analysis

The fixed effects of the treatments on the measured parameters were evaluated by the General Linear Model (GLM) procedure in SPSS 16.0 Statistics (SPSS Inc., Chicago, IL). Means separation between N rates and between planting densities were compared by Least Significant Difference (LSD) at the 0.05 probability level.

The response of a dependent variable to N rate and plant density under film-mulched and non-mulched conditions was fit to a second-order polynomial equation (Han et al., 2013). Data was subjected to establishment of a regression model using SPSS 16.0. Statistics and regression analysis was performed for maize grain yield and WUE during the two growing seasons. The calculation of optimization was done in Matlab 7.1 (MathWorks Inc., Natick, MA).

Table 2. Analysis of variance significance levels for the main factors, mulch practice, N rate, and plant density, the two-way interactions with each other, and the three-way interaction for grain yield, ear numbers per square meter (EN), kernel number per ear (KN), 1000-kernel weight (KW), crop evapotranspiration (ET), and water use efficiency (WUE) in 2013 and 2014.

Sources of variation	Grain yield	EN	KN	KW	ET	WUE
			2013			
Mulch practice (MP)	***	***	**	***	ns	***
Fertilizer rate (N)	***	ns	***	***	***	***
Plant density (PD)	*	***	**	**	**	*
N × PD	ns†	ns	ns	ns	**	*
N × MP	***	ns	**	***	**	**
PD × MP	***	*	ns	*	ns	***
N × PD × MP	**	ns	ns	**	***	ns
			2014			
MP	***	***	**	**	**	***
N	***	ns	***	***	***	***
PD	**	***	**	*	**	**
N × PD	*	ns	*	***	**	*
N × MP	***	ns	***	**	ns	***
PD × MP	*	***	ns	ns	**	*
N × PD × MP	ns	ns	**	**	**	ns

* Significant at $P < 0.05$.
** Significant at $P < 0.01$.
*** Significant at $P < 0.001$.
† ns, not significant at $P \le 0.05$.

RESULTS

Weather Conditions and Growing Periods of Spring Maize

Monthly meteorological data during the two experimental seasons in 2013 and 2014 are presented in Table 1. Total precipitation during the growing seasons was 411 and 375 mm in 2013 and 2014, respectively. Both 2013 and 2014 were wet years, but the distribution of precipitation varied greatly. The majority of the precipitation occurred in July and September and, notably, a heavy rain occurred on 22 July (121 mm, nearly the silking stage) in 2013. In 2014, the majority of the precipitation fell in August and September (milk stage and physiological maturity).

The mean air temperature over the growing season was 20°C in 2013, which was 1°C higher than the mean of 19°C in 2014. The cumulative reference evapotranspiration over the whole growing season was 595 mm in 2013 and 639 mm in 2014. The maize-growing periods lasted 145 to 151 and 144 to 153 d in the two years, respectively.

Grain Yield and Yield Components

In both 2013 and 2014, the fixed effects of mulch practice, N rate, plant density, mulch practice × N rate, and mulch

Table 3. Grain yield, ear number, kernel number per ear, and 1000-kernel weight for different treatments in 2013.

Treatment‡	FM† PD1§	FM† PD2	FM† PD3	FM† Mean	NM PD1	NM PD2	NM PD3	NM Mean
				Grain yield				
				Mg ha^{-1}				
N0	8.3	9.0	9.3	8.9c¶	5.1	5.2	4.2	4.8c
N170	11.7	12.6	12.8	12.3b	8.8	8.4	7.9	8.3a
N200	11.9	13.0	13.7	12.9a	8.3	7.8	7.7	7.9a
N230	11.9	13.1	14.0	13.0a	8.0	7.2	6.0	7.1b
Mean	10.9c	11.9b	12.5a		7.5a	7.1b	6.5c	
				Ear number				
				No. m^{-2}				
N0	5.5	6.5	8.0	6.6a	4.9	6.3	7.4	6.2a
N170	5.4	6.5	7.8	6.6a	5.1	6.5	7.6	6.4a
N200	5.8	6.4	7.9	6.7a	5.2	6.6	7.5	6.4a
N230	5.7	6.5	7.9	6.7a	5.0	6.5	7.7	6.4a
Mean	5.6c	6.5b	7.9a		5.0c	6.5b	7.6a	
				Kernel number				
				No. ear^{-1}				
N0	473	433	434	447c	349	332	314	332c
N170	488	462	446	465b	418	405	386	403a
N200	507	498	465	490a	413	392	361	389ab
N230	512	495	474	494a	399	388	352	380b
Mean	495a	472b	455c		395a	379a	353b	
				Kernel weight				
				g 1000-kernel^{-1}				
N0	326	287	269	294c	202	206	183	197c
N170	358	313	311	327b	254	251	234	246a
N200	361	332	329	341a	240	237	215	231b
N230	349	329	325	335a	238	229	209	225b
Mean	349a	315b	309b		234a	231a	210b	

† FM is the ridge-furrow mulched with plastic film; NM is the ridge-furrow without mulching.

‡ N0, N170, N200, and N230 denote N rates of 0, 170, 200, and 230 kg N ha^{-1}, respectively.

§ PD1, PD2, and PD3 denote planting rates of 50,000, 65,000, and 80,000 plants ha^{-1}, respectively.

¶ Values within a column followed by the same letters do not differ significantly at $p \leq 0.05$.

Table 4. Grain yield, ear number, kernel number per ear, and 1000-kernel weight for different treatments in 2014.

Treatment‡	FM† PD1§	FM† PD2	FM† PD3	FM† Mean	NM PD1	NM PD2	NM PD3	NM Mean
				Grain yield				
				Mg ha^{-1}				
N0	4.6	5.0	5.5	5.0 c¶	4.4	3.2	3.4	3.7d
N170	11.6	12.3	13.2	12.4b	8.5	9.2	9.7	9.1a
N225	13.1	13.9	14.6	13.9a	8.7	8.8	8.7	8.7b
N280	13.7	14.2	14.9	14.3a	7.4	8.2	8.0	7.9c
Mean	10.8c	11.3b	12a		7.2a	7.3a	7.4a	
				Ear number				
				No. m^{-2}				
N0	7.5	8.6	9.7	8.6a	5.8	7.5	9.4	7.6a
N170	7.5	8.4	9.9	8.6a	6.0	7.5	9.6	7.7a
N225	7.7	8.5	9.9	8.7a	5.8	7.7	9.5	7.7a
N280	7.6	8.6	9.7	8.7a	6.0	7.6	9.3	7.6a
Mean	7.6c	8.5b	9.8a		5.9c	7.6b	9.4a	
				Kernel number				
				No. ear^{-1}				
N0	287	180	173	213b	200	197	161	186c
N170	529	503	441	491a	475	455	404	444a
N225	499	501	480	493a	433	414	367	404b
N280	520	508	456	495a	441	381	342	388b
Mean	459a	423b	387c		387a	362b	318c	
				Kernel weight				
				g 1000-kernel^{-1}				
N0	238	237	254	243c	226	193	201	206b
N170	310	290	285	295b	296	274	246	272a
N225	323	311	298	310a	273	262	247	261a
N280	337	312	309	319a	262	255	248	255a
Mean	302a	287ab	286b		264a	246ab	236b	

† FM is the ridge-furrow mulched with plastic film; NM is the ridge-furrow without mulching.

‡ N0, N170, N225, and N280 denote N rates of 0, 170, 225, and 280 kg N ha^{-1}, respectively.

§ PD1, PD2, and PD3 denote planting rates of 50,000, 65,000, and 80,000 plants ha^{-1}, respectively.

¶ Values within a column followed by the same letters do not differ significantly at $p \leq 0.05$.

practice × plant density were significant for grain yield. The N rate × plant density interaction was significant ($P < 0.05$) only in 2014. The N rate × plant density × mulch practice interaction was significant ($P < 0.01$) only in 2013 (Table 2).

The average grain yield in FM was 11.8 and 11.4 Mg ha^{-1} in 2013 and 2014, respectively, a significant increase of 67 and 55%, compared with NM (Tables 3 and 4). For the different plant densities, grain yield was significantly higher in the N-fertilized treatments than in the N0 treatments. The yield increases were 40 to 51% and 140 to 197% in FM for 2013 and 2014, respectively, and 40 to 88% and 69 to 186% in NM for 2013 and 2014, respectively. The response of grain yield to N supply varied greatly under the two mulch practices. For FM, averaged across plant densities, grain yield increased with N rate increase in both years, but no significant difference was observed when the N rate was increased from 200 to 230 kg N ha^{-1} in 2013 and from 225 to 280 kg N ha^{-1} in 2014. For NM, application of >170 kg N ha^{-1} consistently failed to further improve grain yield in both years (Tables 3 and 4).

The response of grain yield to plant density also varied significantly under the two mulch practices. For FM, averaged across N rates, grain yield increased with increasing plant density in both years. The yield increases were 9 and 5% for PD2 versus PD1 in 2013 and 2014, respectively, and 15 and 11% for PD3 versus PD1 in 2013 and 2014, respectively. For NM, grain yield in PD2 and PD3 were 5 and 13% lower than in PD1 in 2013, respectively, but no significant ($P > 0.05$) differences were observed among the three plant densities in 2014 (Tables 3 and 4).

Similar to the response of grain yield, FM significantly increased the average kernel number per ear (KN) by 26% in 2013 and 19% in 2014 and 1000-kernel weight (KW) by 44% in 2013 and 17% in 2014, as compared with NM (Tables 3 and 4). The N rate and mulch practice ′ N rate interaction had a significant effect on KN and KW in both years (Table 2). Both KN and KW were significantly higher in the N-fertilized treatments than in the N0 treatments under the two mulch practices regardless of plant density. It is noteworthy that both KN and KW increased as N rate increased in FM; however, in NM, the application of >170 kg N ha^{-1} resulted in a reduction in KN and

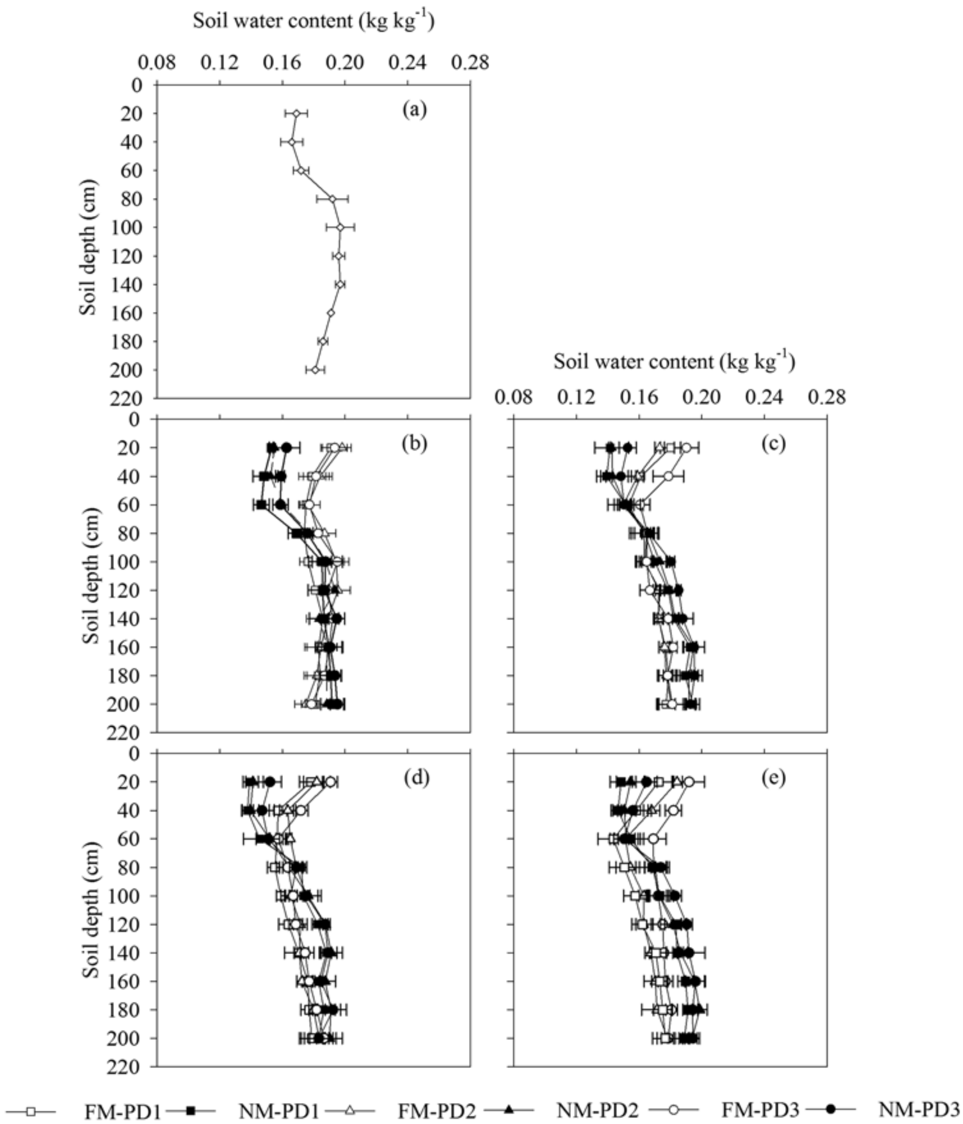

Fig. 1. Soil water content in 2013 in the top 200 cm of the soil profile before planting (PT, a) and at harvest (R6, b-e) under two mulch practices (FM, the ridge-furrow mulched with plastic film; NM, the ridge-furrow without mulching), four N rates (b, 0 kg N ha^{-1}; c, 170 kg N ha^{-1}; d, 200 kg N ha^{-1}; e, 230 kg N ha^{-1}), and three plant densities (PD1, 50,000 plants ha^{-1}; PD2, 65,000 plants ha^{-1}; PD3, 80,000 plants ha^{-1}). Bars are one standard deviation of the mean (n = 3).

KW. Plant density had a significant effect on the yield components KN, KW, and EN (ear number m^{-2}) in both years, while the mulch practice × plant density interaction was significant for EN in the two years and for KW (P < 0.05) only in 2013 (Table 2). Across all N rates, values for KN and KW decreased as plant density increased under both mulch practices. In contrast, increased plant density was accompanied by higher values of EN.

Dynamics and Balance of Soil Moisture

Soil water content in the top 200 cm profile measured before planting and at harvest in the two years is shown in Figs. 1 and 2. In 2013 at harvest, soil water content markedly increased at 0- to 40-cm soil depth for FM and at 180- to 200-cm soil depth for NM, compared with the levels at planting (Fig. 1a–e). Soil water content in FM was significantly higher at 0- to 60-cm soil depth than it was in NM. The opposite situation was found at 80- to 200-cm soil depth, regardless of N rate and plant density (Fig. 1c–e). The response of soil water content to N supply varied greatly under the two mulch practices. For FM, the average soil water content across all plant densities in N0 was significantly higher than in the N-fertilized treatments at 0- to 180-cm soil depth, and no significant differences were found among N-fertilized treatments. In NM, the average soil water content was significantly higher in N0 than in the N-fertilized treatments at 80- to 120-cm soil depth. Averaged across all plant densities, soil water storage in the 0- to 200-cm profile at harvest for film-mulched maize increased by 1 mm in N0 but decreased by 35 to 39 mm in the N-fertilized treatments, compared with the levels before planting. The corresponding values for non-mulched maize decreased by 11 to 26 mm in N0 and by 14 to 41 mm in the N-fertilized treatments (Table 5).

In 2014 at planting, soil water content in FM was significantly higher than in NM at 0- to 140-cm soil depth, regardless of N rate and plant density factors (Fig. 2a–d). At harvest, soil water content at 160- to 200-cm soil depth was significantly higher in NM than in FM, excepted for the N0 treatment. In both FM and NM, across all plant densities, soil water content in N0 was significantly higher than in the N-fertilized treatments at 100- to 200-cm soil

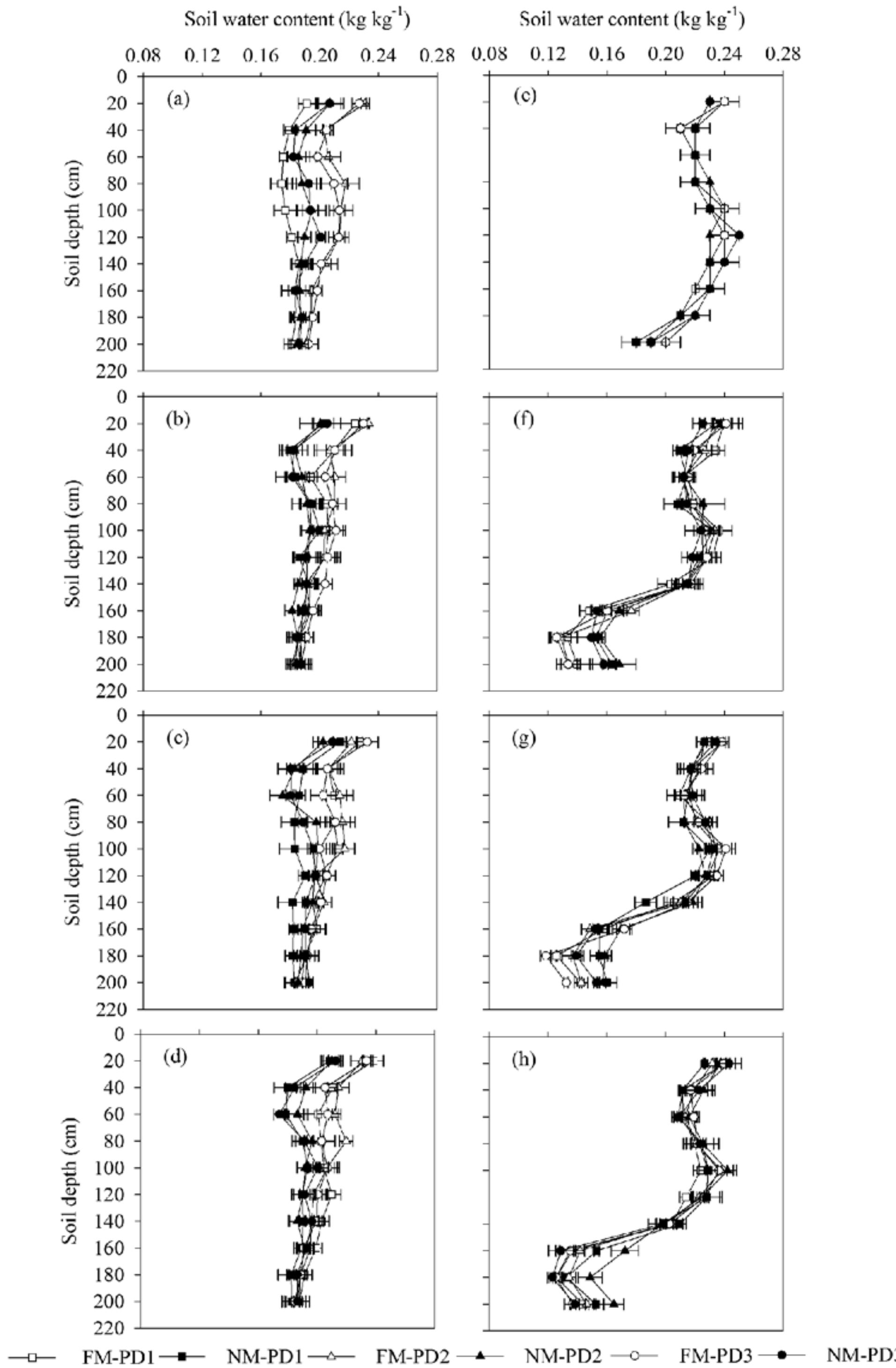

Fig. 2. Soil water content in 2014 in the top 200 cm of the soil profile before planting (PT, a-d) and at harvest (R6, e-h) under two mulch practices (FM, the ridge-furrow mulched with plastic film; NM, the ridge-furrow without mulching), four N rates (a and e, 0 kg N ha^{-1}; b and f, 170 kg N ha^{-1}; c and g, 225 kg N ha^{-1}; d and h, 280 kg N ha^{-1}), and three plant densities (PD1, 50,000 plants ha^{-1}; PD2, 65,000 plants ha^{-1}; PD3, 80,000 plants ha^{-1}). Bars are one standard deviation of the mean (n = 3).

depth (Fig. 2e–h). Across all N rates, soil water content in PD2 was significantly higher than in PD1 and PD3 at 160- to 200-cm soil depth, but only for NM. Overall, for FM, soil water storage in 0- to 200-cm profile at harvest, averaged across all plant densities, increased by 52 mm in N0 but decreased by 6 to 21 mm in the N-fertilized treatments, as compared with the levels before planting. The corresponding values for NM increased by 84 mm in N0 and by 23 to 34 mm in the N-fertilized treatments (Table 6).

Evapotranspiration and Water Use Efficiency

The total ET over the whole maize growing season varied in the range of 406 to 466 and 284 to 404 mm in 2013 and 2014, respectively. The ET did not respond to mulch practice in 2013; however, in 2014 ET in FM was significantly (P < 0.01) higher than in NM for each N rate and plant density. The N rate, and interactions with mulch practice and plant density, were significant in both 2013 and 2014 for ET (Table 2). In both FM and

Table 5. Soil water storage before planting (PT) and at harvest (R6), evapotranspiration, and water-use efficiency for different treatments in 2013.

	FM†				NM			
Treatment‡	PD1§	PD2	PD3	Mean	PD1	PD2	PD3	Mean
				Soil water storage at PT				
				mm				
N0	481	481	481	481a¶	481	481	481	481a
N170	481	481	481	481a	481	481	481	481a
N200	481	481	481	481a	481	481	481	481a
N230	481	481	481	481a	481	481	481	481a
Mean	481a	481a	481a		481a	481a	481a	
				Soil water storage at R6				
				mm				
N0	472	487	487	482a	455	462	470	462a
N170	443	440	455	446b	443	447	456	449b
N200	436	449	453	446b	440	448	451	446b
N230	462	436	427	442b	450	457	467	458ab
Mean	453a	453a	456a		447b	453ab	461a	
				Evapotranspiration				
				mm				
N0	421	406	406	411b	438	431	423	431a
N170	450	453	437	447a	450	446	436	444a
N200	457	443	439	447a	453	445	442	447a
N230	431	457	466	451a	443	436	426	435a
Mean	440a	440a	437a		446a	439a	432a	
				Water use efficiency				
				kg ha^{-1} mm^{-1}				
N0	19.7	22.2	22.8	21.6c	11.5	12.0	9.9	11.1d
N170	25.9	27.8	29.2	27.6b	19.5	18.8	18.1	18.8a
N200	26.1	29.3	31.3	28.9a	18.3	17.6	17.4	17.7b
N230	27.7	28.7	30.1	28.8a	18.1	16.6	14.2	16.3c
Mean	24.8c	27.0b	28.4a		16.9a	16.2b	14.9c	

† FM is the ridge-furrow mulched with plastic film; NM is the ridge-furrow without mulching.

‡ N0, N170, N200, and N230 denote N rates of 0, 170, 200, and 230 kg N ha^{-1}, respectively.

§ PD1, PD2, and PD3 denote planting rates of 50,000, 65,000, and 80,000 plants ha^{-1}, respectively.

¶ Values within a column followed by the same letters do not differ significantly at $p \leq 0.05$.

Table 6. Soil water storage before planting (PT) and at harvest (R6), evapotranspiration, and water use efficiency for different treatments in 2014.

	FM†				NM			
Treatment‡	PD1§	PD2	PD3	Mean	PD1	PD2	PD3	Mean
				Soil water storage at PT				
				mm				
N0	529	540	536	535a¶	506	496	497	500a
N170	523	528	535	528a	496	491	496	494a
N225	533	534	531	533a	489	498	500	496a
N280	535	535	528	533a	492	502	500	498a
Mean	530a	534a	532a		496a	497a	498a	
				Soil water storage at R6				
				mm				
N0	581	592	587	587a	580	587	585	584a
N170	523	524	520	522b	526	537	520	528b
N225	519	523	526	523b	518	530	527	525b
N280	506	516	513	512b	517	538	509	521b
Mean	532a	539a	537a		535b	548a	535b	
				Evapotranspiration				
				mm				
N0	323	323	324	323c	302	284	287	291b
N170	376	379	390	381b	345	329	352	342a
N225	390	387	380	386b	346	343	348	346a
N280	404	395	390	397a	350	340	366	352a
Mean	373a	371a	371a		336a	324b	338a	
				Water use efficiency				
				kg ha^{-1} mm^{-1}				
N0	14.3	15.5	17.0	15.6c	14.6	11.3	11.8	12.6d
N170	31.0	32.4	33.9	32.4b	24.6	27.9	27.5	26.7a
N225	33.6	35.9	38.4	36.0a	25.1	25.6	25.1	25.3b
N280	34.0	35.9	38.1	36.0a	21.2	24.1	21.7	22.3c
Mean	28.2c	29.9b	31.9a		21.4a	22.2a	21.5a	

† FM is the ridge-furrow mulched with plastic film; NM is the ridge-furrow without mulching.

‡ N0, N170, N225, and N280 denote N rates of 0, 170, 225, and 280 kg N ha^{-1}, respectively.

§ PD1, PD2, and PD3 denote planting rates of 50,000, 65,000, and 80,000 plants ha^{-1}, respectively.

¶ Values within a column followed by the same letters do not differ significantly at $p \leq 0.05$.

NM, averaged across all plant densities ET in the N-fertilized treatments was significantly higher than in N0, except for NM in 2013. Averaged across N rates ET in PD2 was lower than in the PD1 and PD3 treatments under non-mulched conditions in 2014.

Response of WUE was similar to grain yield

The fixed effects of mulch practice, N rate, plant density, and two-way interactions with each other on WUE were significant in both 2013 and 2014 (Table 2). The average WUE in FM was 26.7 and 30.0 kg ha^{-1} mm^{-1} in 2013 and 2014, respectively, which was a significant increase of 67 and 38%, respectively, compared with NM. Averaged across all plant densities, the WUE in FM almost consistently increased with N rate increase in each year. Specifically, the WUE values in the N170, N200, and N230 treatments in 2013 were 28, 34, and 34% higher than in N0, respectively, and the WUE values in N170, N225, and N280 in 2014 were 108, 131, and 131% higher than N0, respectively. For NM, the WUE first increased and then decreased as N rate increased, and the highest WUE for maize was in the N170 treatment (Tables 5 and 6). Averaged across all N rates, the WUE in FM increased markedly with the increase in plant density in each year; the WUE in PD2 and PD3 were 9 and 15% higher in 2013 and 6 and 13% higher in 2014, respectively, as compared with PD1. For NM, the WUE decreased significantly as plant density increased in 2013. Specifically, the WUE in PD2 and PD3 were 4 and 12% lower than PD1 in 2013, respectively (Tables 5 and 6).

Regression Analysis for Grain Yield and Water Use

To determine the optimum N fertilizer level and the ideal plant density under film-mulched conditions, a regression analysis was performed for maize grain yield and WUE during the two growing seasons (Fig. 3 and 4; Table 7). The response surfaces showed that the combined effect of N supply and plant density on grain yield and WUE differed between FM and NM (Fig. 3a-d and 4a-d).

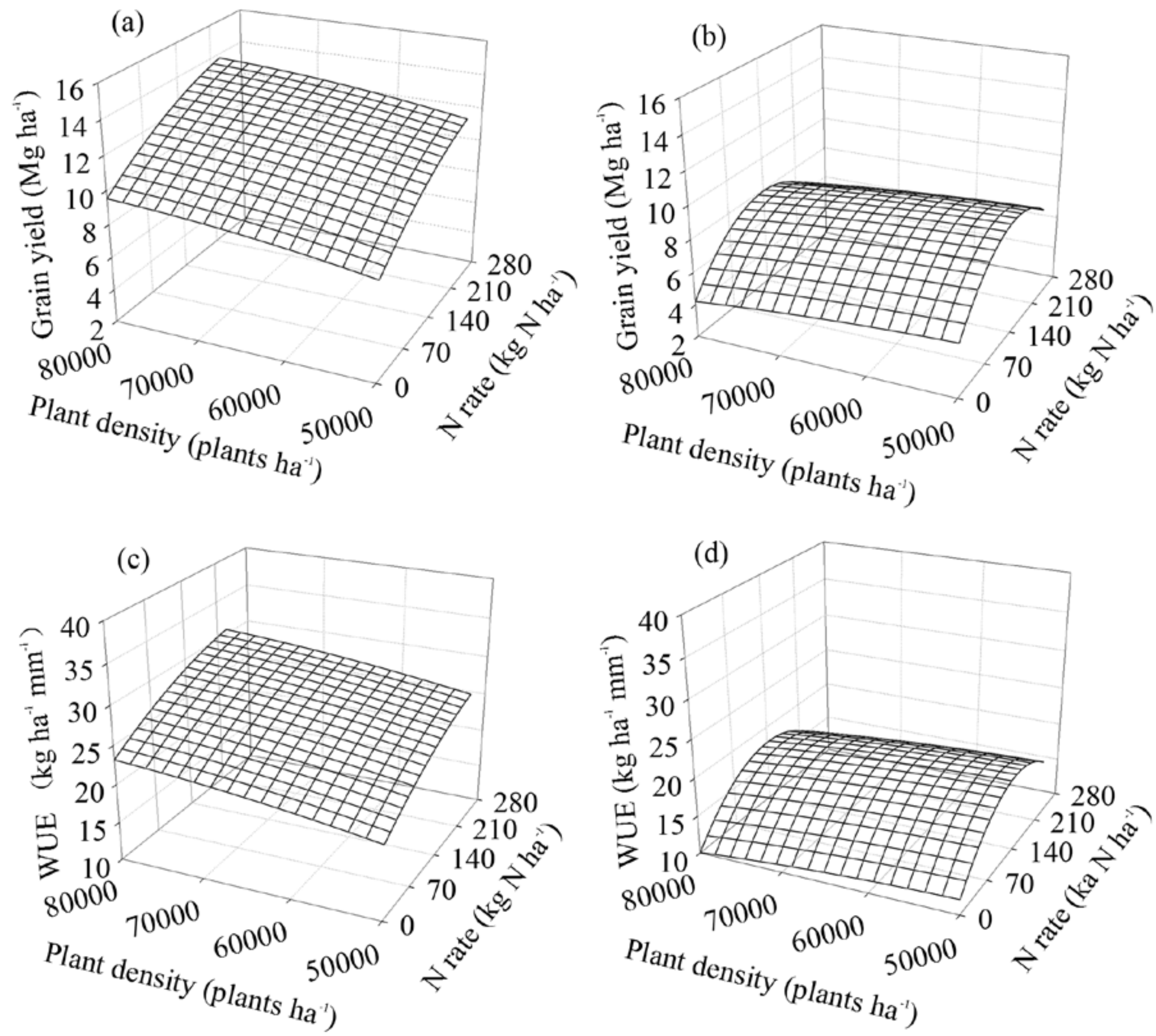

Fig. 3. Response surfaces showing the effect of N rate and plant density on grain yield (Mg ha^{-1}) (a, FM, the ridge-furrow mulched with plastic film; b, NM, the ridge-furrow without mulching) and water use efficiency (WUE, kg ha^{-1} mm^{-1}) (c, FM; d, NM) when maize was grown under two mulching practices in 2013.

For FM, grain yield increased with increasing N rate and plant density (Fig. 3a and 4a). In both years, grain yield was lowest in the 0 N kg ha^{-1} and 50,000 plants ha^{-1} treatment combinations. The predicted maximum grain yield was 14.3 and 15.1 Mg ha^{-1} in 2013 and 2014 (280 N kg ha^{-1} and 80,000 plants ha^{-1}), respectively. For NM, grain yield increased, reached a maximum, and then decreased with increasing N rate and plant density (Fig. 3b and 4b). The lowest grain yield was obtained in the 0 N kg ha^{-1} and 80,000 plants ha^{-1} treatment combinations. The predicted maximum yield for NM was 9.0 Mg ha^{-1} (144 N kg ha^{-1} and 50,000 plants ha^{-1}) and 9.3 Mg ha^{-1} (198 N kg ha^{-1} and 80,000 plants ha^{-1}), which was 37 and 38% lower than that for FM in 2013 and 2014, respectively (Table 8).

Variation in WUE followed a trend similar to that for grain yield in both FM and NM (Fig. 3c-d and 4c-d). When the predicted yield was highest, WUE in FM was 31.3 and 38.4 kg ha^{-1} mm^{-1} in 2013 and 2014, respectively, which were increases of 58 and 46% compared with NM (Table 8).

DISCUSSION

Field management practices affect soil moisture and thermal status, which play an important role in crop yield and WUE in dryland farming (Zhang et al., 2011). In the present study, grain yield in the film-mulched (FM) treatments was significantly higher than it was in the non-mulched (NM) treatments. The better temperature-water conditions under film mulching, especially at the early growth stage, may have promoted seedling emergence and crop development (Anikwe et al., 2007; Zhou et al., 2009), leading to reproductive success and final yield increases (Gan et al., 2013). In 2013 at harvest, the average soil water content in FM was significantly higher at 0- to 60-cm soil depth compared with NM; the opposite situation was observed at 80- to 200-cm soil depth. This can be explained by the favorable temperature-water conditions under the film mulching that supported vigorous plant growth, allowing them to exploit more soil water in deep layers than in NM (Zhou et al., 2009; Li et al., 2015). In 2014, the soil water content at 160- to 200-cm soil depth was higher in NM than in FM. This may be associated with a few high-intensity rain events that occurred around mid-September (approximately physiological maturity), which led to more rainwater infiltration in the bare ridges (Li et al., 2008). Together, higher temperatures and increased water content under film mulching significantly promoted plant growth and development (Bu et al., 2013; Liu et al., 2014b), markedly

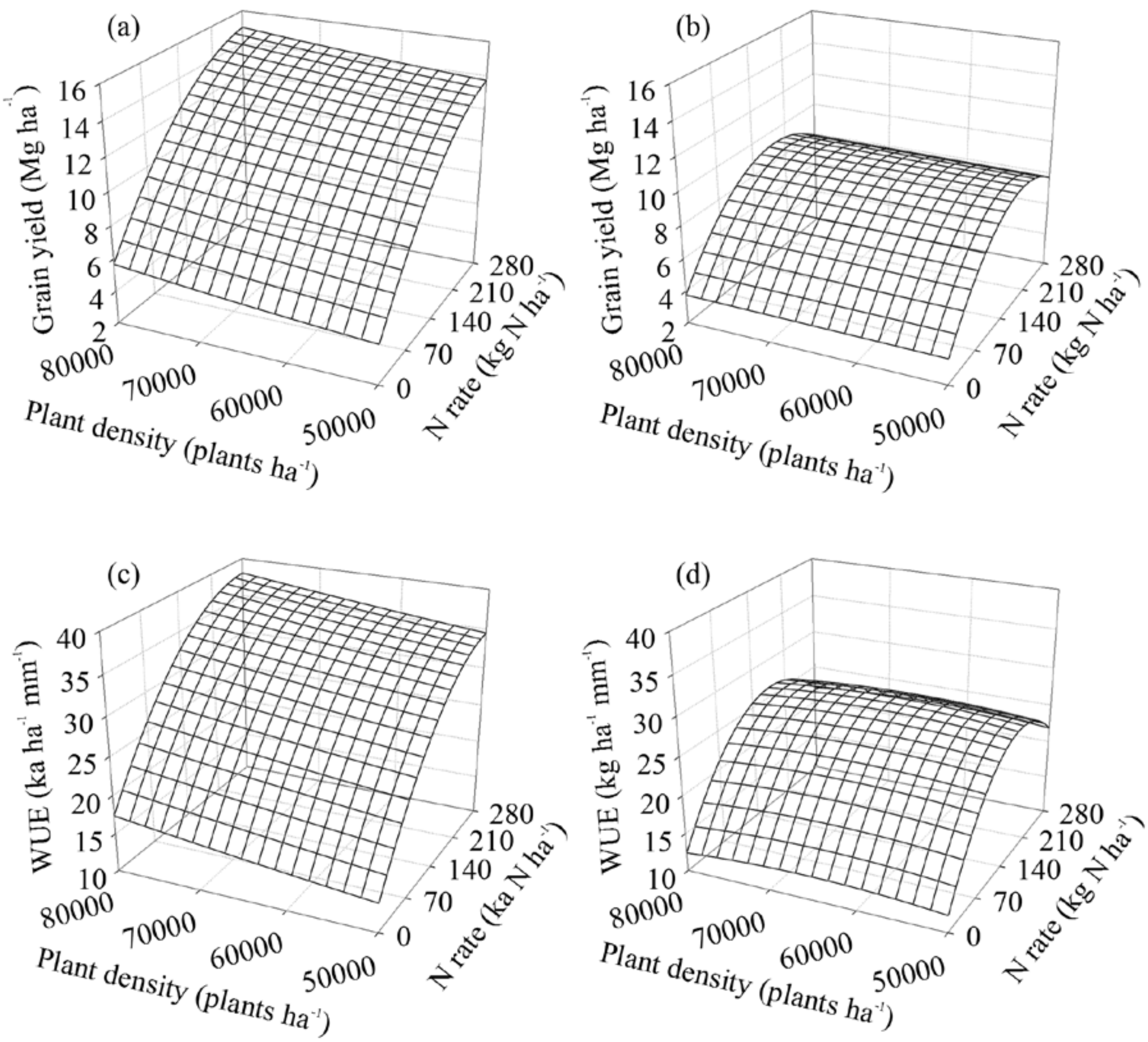

Fig. 4. Response surfaces showing the effect of N rate and plant density on grain yield (Mg ha^{-1}) (a, FM, the ridge-furrow mulched with plastic film; b, NM, the ridge-furrow without mulching) and water use efficiency (WUE, kg ha^{-1} mm^{-1}) (c, FM; d, NM) when maize was grown under two mulching practices in 2014.

increased yield components (KN and KW), and thus led to the final increases in grain yield.

Higher grain yields under film mulching are always associated with higher WUE (Zhou et al., 2009; Liu et al., 2014a). In the present study, the ET was almost identical between FM and NM in 2013. The reason may be that film mulching reduces water loss by evaporation, while it increases water use by transpiration (Lascano et al., 1994; Li et al., 2015). In 2014, FM had a remarkably higher ET than NM due to higher soil water storage prior to planting. However, the WUE in FM was significantly higher than it was in NM in both years. Under film mulching, increases in precipitation use efficiency and reduction in soil evaporation would increase the amount of water passing through the crop via transpiration (Gan et al., 2013; Willis et al., 1963), leading to higher WUE. Our results showed that, over the two growing seasons, the average grain yield ranged from 11.4 to 11.8 Mg ha^{-1}, and WUE ranged from 26.7 to 30.0 kg ha^{-1} mm^{-1} for FM maize. These results are generally higher than the average grain yield of 8.5 to 9.1 Mg ha^{-1} and WUE of 18.7 to 23.4 kg ha^{-1} mm^{-1} for irrigated maize (Kim et al., 2008), reinforcing the effective use of FM tillage in dryland farming areas.

The N-fertilized treatments had significantly increased grain yield compared with N0 in both FM and NM, indicating that N fertilizer application is effective to increase grain yield under film-mulched and non-mulched conditions in the study region. An adequate N supply in N deficient soils remarkably promoted plant growth, increased leaf area and leaf area index, and thus led to a significant increase in above-ground biomass (Li et al., 2015). High biomass production during the reproductive stage increased the final KN and KW (Roth et al., 2013). Consequently, the differences in grain yield can be attributed to different yield components (KN and KW) with four N rates under two mulch practices.

In addition, N fertilizer application reduced soil water storage in the 0- to 200-cm profile after maize harvest, especially in FM. One explanation for this observation is that N fertilization improved root growth and increased shoot biomass, thus reducing evaporation but increasing transpiration (Hernández et al., 2015; Li et al., 2015). These effects are in agreement with the higher ET observed in the N-fertilized treatments compared with N0 in this work. However, averaged across all plant densities, application of >170 kg N ha^{-1} did not consistently increase ET, indicating that increase in WUE under N-fertilized treatments was attributable to differences in yield.

Table 7. Regression equations for the response variables of grain yield and water use efficiency (WUE) with N rates and plant densities under film-mulched and non-mulched conditions in 2013 and 2014.

Mulch practice†	Response variable	Regression equation‡	R^2§
2013			
FM	Grain yield	$y = 2.868 + 0.02x_1 + (1.60\times10^{-4})x_2 - (4.61\times10^{-4})x_1^2 - (1.00\times10^{-9})x_2^2 + (1.36\times10^{-7})x_1x_2$	0.994***
	WUE	$y = 7.271 + 0.047x_1 + (3.39\times10^{-4})x_2 - (7.87\times10^{-5})x_1^2 - (1.78\times10^{-9})x_2^2 + (5.56\times10^{-8})x_1x_2$	0.976***
NM	Grain yield	$y = 3.753 + 0.057x_1 + (6.15\times10^{-5})x_2 - (1.85\times10^{-4})x_1^2 - (6.67\times10^{-10})x_2^2 - (7.65\times10^{-8})x_1x_2$	0.973***
	WUE	$y = 7.087 + 0.118x_1 + (1.74\times10^{-4})x_2 - (3.75\times10^{-4})x_1^2 - (1.67\times10^{-9})x_2^2 - (1.52\times10^{-7})x_1x_2$	0.972***
2014			
FM	Grain yield	$y = 3.676 + 0.057x_1 + (5.75\times10^{-6})x_2 - (9.64\times10^{-5})x_1^2 + (2.22\times10^{-10})x_2^2 + (5.15\times10^{-8})x_1x_2$	0.999***
	WUE	$y = 12.019 + 0.131x_1 + (2.08\times10^{-5})x_2 - (2.53\times10^{-4})x_1^2 + (5.00\times10^{-10})x_2^2 + (2.08\times10^{-7})x_1x_2$	0.997***
NM	Grain yield	$y = 5.211 + 0.046x_1 - (2.36\times10^{-5})x_2 - (1.52\times10^{-4})x_1^2 + (6.35\times10^{-24})x_2^2 + (1.79\times10^{-7})x_1x_2$	0.978***
	WUE	$y = 2.644 + 0.128x_1 + (3.85\times10^{-4})x_2 - (4.29\times10^{-4})x_1^2 - (3.44\times10^{-9})x_2^2 + (4.03\times10^{-7})x_1x_2$	0.965***

*** Significant at the 0.001 probability level.

† FM is the ridge-furrow mulched with plastic film; NM is the ridge-furrow without mulching.

‡ y is grain yield (Mg ha^{-1}) or water use efficiency (WUE, kg ha^{-1} mm^{-1}); x_1 is N rate; x_2 is plant density.

§ R^2 is the coefficient of determination.

Table 8. Optimization of N application rate and plant density based on maximum grain yield (Mg ha^{-1}) and water use efficiency (WUE, kg ha^{-1} mm^{-1}) under film-mulched and non-mulched conditions in 2013 and 2014.

Mulch practice†	Response variable	Maximum	N rate	Plant density
			kg N ha^{-1}	plants ha^{-1}
2013				
FM	Grain yield (Mg ha^{-1})	14.3	280	80,000
	WUE (kg ha^{-1} mm^{-1})	31.3	280	80,000
NM	Grain yield (Mg ha^{-1})	9.0	144	50,000
	WUE (kg ha^{-1} mm^{-1})	19.8	147	50,000
2014				
FM	Grain yield (Mg ha^{-1})	15.1	280	80,000
	WUE (kg ha^{-1} mm^{-1})	38.4	280	80,000
NM	Grain yield (Mg ha^{-1})	9.3	198	80,000
	WUE (kg ha^{-1} mm^{-1})	27.0	181	66,537

† FM is the ridge-furrow mulched with plastic film; NM is the ridge-furrow without mulching.

Previous research demonstrated that synergistic relationships exist between water and N, with N addition improving WUE and water addition improving N use efficiency (Kim et al., 2008). Our study confirmed that grain yield and WUE are influenced by an interaction between mulch practice and N supply. Higher amounts of N fertilizer were required to maximize productivity in FM compared with NM. These findings mean that adjusting the optimum amount of N is important to improve grain yield and WUE when FM tillage is applied.

The response of maize grain yield to plant density has been described as fitting a typical quadratic equation with an optimum value (Tokatlidis and Koutroubas, 2004). In our study, improved soil water storage during the seedling growth stage in FM could support higher plant density (80,000 plants ha^{-1}) to increase grain yield. In NM, low rainfall early in the growing season did not permit adequate water demand to support the higher plant density, and thus plant populations of >50,000 plants ha^{-1} failed to further improve grain yield in each growing season. Cox (1996) and Tokatlidis et al. (2011) reported that maize hybrids did not tolerate density stress under water stress conditions. The lack of a soil water storage response in the 0- to 200-cm profile before planting and at harvest to plant density was in agreement with the lack of ET response to plant density. Consequently, the response of WUE to plant density was consistent with that of grain yield in both FM and NM. In our study, grain yield and WUE responses in both years demonstrated significant interaction effects between mulch practice and plant density. The optimum plant density for populations grown under FM conditions was much higher than when grown under NM conditions. The variation in optimum plant density with grain yield and WUE under contrasting conditions of water availability (i.e., rain-fed vs. irrigated) has been documented by Kiniry et al. (2002) and Tokatlidis et al. (2011).

Furthermore, the response surfaces showed that predicted maximum yield and WUE varied greatly between the two years of study for both FM and NM. This is mostly related to different weather conditions during the growing seasons. An added crop stress in the 2013 growing season was a heavy rain with strong winds that occurred on 22 July (121 mm, approximately silking stage), causing the plants to lodge, and thus decreasing grain yield. Yield increases in modern maize hybrids have largely been associated with the interaction between ideal plant density and N availability (Tollenaar and Lee, 2002). Highly productive maize hybrids displayed limited tolerance to the simultaneous stresses of intense crowding and low fertilizer N availability (Boomsma et al., 2009). This is especially true for NM in the 0 N kg ha^{-1} and 80,000 plants ha^{-1} treatment combinations in the present study. Boomsma et al. (2009) reported 5.2 to 7.0 Mg ha^{-1} yield responses to optimal and supraoptimal plant densities (79,000 and 10,400 plants ha^{-1}) and a side-dress N rate of 165 kg N ha^{-1}. In the present study, the potential maximum grain yield (14.3 and 15.1 Mg ha^{-1} in 2013 and 2014, respectively) in FM was obtained with a combination of 280 kg N ha^{-1} and 80,000 plants ha^{-1}. Nevertheless, this management combination may slightly vary with soil moisture. A study demonstrated that FM maize in similar soils reached its maximum yield value with the equivalent level of N (Liu et al., 2010). However, in our study, there was no significant difference in grain yield between the 280 and 225 kg N ha^{-1} treatments. This means that application of 225 kg N ha^{-1} met the N demand of FM maize. Overuse of N fertilizer could cause nitrate (NO_3^--N) accumulation in the soil profile (Liu et al., 2014a) and decreased N use efficiency (Liu et al., 2013). We recommend the use of mulching tillage with ridge-furrow together with 225 kg N ha^{-1} and 80,000 plants ha^{-1}

to improve maize grain yield and WUE in semiarid regions (>94% of the potential maximum grain yield and WUE).

CONCLUSIONS

Compared with the NM system, the FM system for maize cultivation improved soil water content. Mulch practice ′ N rate and mulch practice ′ plant density interactions existed for yield and WUE. Notably, FM required a higher N rate (280 kg N ha^{-1}) and higher plant density (80,000 plants ha^{-1}) for maximum grain yield and WUE than the NM treatments. Although the theoretical maximum yield was observed for N280, the high N rate resulted in a low N use efficiency. In comparison, a lower N rate (225 kg N ha^{-1}) yielded 94% of the maximum and greatly improved N use efficiency in maize.

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