Increased photosynthesis and grain yields in maize grown with less irrigation water combined with density adjustment in semiarid regions

Donghua Liu[1,2,3], Qianmin Jia[4], Juan Li[1,2,3], Peng Zhang[1,2,3], Xiaolong Ren[1,2,3] and Zhikuan Jia[1,2,3]

[1] College of Agronomy, Northwest A&F University, Yingling, China
[2] Institute of Water Saving Agriculture in Arid Areas of China, Northwest A&F University, Yingling, China
[3] Key Laboratory of Crop Physi-ecology and Tillage Science in North-western Loess Plateau, Ministry of Agriculture, Northwest A&F University, Yingling, China
[4] State Key Laboratory of Grassland Agro-Ecosystems, Key Laboratory of Grassland Livestock Industry Innovation, Ministry of Agriculture, China, College of Pastoral Agriculture Science and Technology, Lanzhou University, Lanzhou, China

ABSTRACT

In order to design a water-saving and high-yield maize planting model suitable for semiarid areas, we conducted trials by combining supplementary irrigation with different planting densities. Three planting densities (L: 52,500, M: 75,000, and H: 97,500 plants ha^{-1}) and four supplementary irrigation modes (NI: no irrigation; IV: 375 m^3 ha^{-1} during the 11-leaf stage; IS: 375 m^3 ha^{-1} in the silking stage; and IVS: 375 m^3 ha^{-1} during both stages) were tested. The irrigation treatments significantly increased the leaf relative water content, but the high planting density significantly decreased the relative water content during the silking and filling stages. After supplementary irrigation during the 11-leaf stage, IV and IVS significantly increased the photosynthetic capacity, but decreased the leaf water use efficiency. IS and IVS significantly increased the photosynthetic capacity after supplementary irrigation in the silking stage over two years. During the filling stage, IV, IS, and IVS increased the two-year average net photosynthetic rate by 17.0%, 27.2%, and 30.3%, respectively. The intercellular CO_2 concentration increased as the density increased, whereas the stomatal conductance, transpiration rate, net photosynthetic rate, and leaf water use efficiency decreased, and the high planting density significantly reduced the leaf photosynthetic capacity. The highest grain yield was obtained using the IVS treatment under the medium planting density, but it did not differ significantly from that with the IS treatment. Furthermore, the IVS treatment used two times more water than the IS treatment. Thus, the medium planting density combined with supplementary irrigation during the silking stage was identified as a suitable water-saving planting model to improve the photosynthetic capacity and grain yield, and to cope with drought and water shortages in semiarid regions.

Subjects Agricultural Science, Ecology, Plant Science
Keywords Rainfall harvesting, Net photosynthetic rate, Supplemental irrigation, Climate change, Density

INTRODUCTION

Water resources are severely deficient in the arid and semiarid regions of northwestern China (*Çakir, 2004*; *Du et al., 2010*), and thus groundwater has become a major source of agricultural irrigation water in the region. However, the extensive use of groundwater resources has led to serious consequences, such as the continued decline in groundwater levels, reduced vegetation area, soil salinization, and desertification (*Kang & Zhang, 2004*; *Wang et al., 2012*). The availability of water resources will decline under climate change (*Dai et al., 2010*), thereby posing a huge challenge to food security in the region (*Kang, 2017*). Therefore, there is an urgent need to adopt water-saving irrigation technologies to use rainfall resources in a rational manner and increase crop yields in the region.

The ridge and furrow rainfall harvesting system (RFS) is a water-collecting agricultural technique, which involves constructing ridges spaced at a set distance within the field, covering the ridges, and then planting crops in the furrows. In RFS, the furrows and ridges are connected, so precipitation that runs off from the surface of the ridge is collected in the furrow where it can be utilized by the crop (*Wang et al., 2014*). Due to its efficient rainfall collection and preservation features, RFS has become one of the main water-saving measures used for agricultural production in arid and semiarid regions. (*Gan et al., 2013*; *Hu et al., 2014*; *Wang et al., 2015*).

However, the low rainfall in the arid regions of northwestern China means that the rainfall collected using RFS cannot meet the requirements for further increasing maize yields. Thus, large areas of farmland still require irrigation in order to increase maize yields (*Wu et al., 2015*). The introduction and application of water-saving irrigation techniques is an effective approach for increasing maize yields in northwestern China (*Lian et al., 2016*). Supplementary irrigation is an important agricultural water-saving measure because it can provide the appropriate amount of water during critical crop growth stages, although the water stress in stages where crops require less water to promote root growth are not considered (*Xue et al., 2003*; *Eapen et al., 2005*). Supplementary irrigation enhances the ability of crops to withstand drought (*Potters et al., 2007*; *Zhou et al., 2009*), and ultimately increases the grain yield and water use efficiency (*Fabeiro, Olalla & Juan, 2001*; *Du et al., 2010*).

Photosynthesis is the basis of maize crop development and more than 80% of the dry matter in maize comes from photosynthesis (*Echarte, Rothstein & Tollenaar, 2008*; *Morot-Gaudry, 1986*). The planting density significantly affects the canopy structure and photosynthetic rate in maize (*Li & Li, 2004*), as well as affecting the accumulation and distribution of dry matter (*Echarte & Andrade, 2003*; *Sarlangue et al., 2007*). At present, the key measure used to obtain maize high yields in large areas is to increase the planting density, which is a relatively simple method (*Ren, Sun & Wang, 2016*). Increasing the plant density maximizes the use of light, water, and heat to achieve the maximum grain yield per unit area (*Ren et al., 2017*; *Timlin et al., 2014*). Many studies suggest that increasing the planting density within a certain range can significantly increase the leaf area index and dry matter accumulation, thereby achieving high maize yields (*Ren et al., 2017*; *Li & Li, 2004*). However, an excessive planting density can lead to growth depression within the

maize population, as well as resulting in poor ventilation, decreased light transmission, and accelerated leaf senescence (*Borrás, Maddonni & Otegui, 2003*), thereby reducing the net photosynthetic rate (Pn) (*Lin et al., 2016*). An excessively high planting density will also consume a large amount of the soil moisture, which can cause water stress and lead to various molecular, biochemical, and physiological changes in plants, thereby affecting growth and development (*Zhu, Shi & Li, 2001*; *Farooq, Mubshar & Kadambot, 2014*). For example, water stress can affect the plant leaf relative water content, leaf stomatal conductance (Gs), intercellular carbon dioxide concentration (C_i), non-photosynthetic organ carbon partitioning, and osmotic protective compounds (*Chaves, 2002*), thereby inhibiting photosynthesis (*Chen & Hao, 2015*). Water stress also increases the anthesis-silking interval (*Bolaños & Edmeades, 1996*), decreases the silk growth rate, and reduces the growth time to ultimately cause drought-related abortion and reduce grain yields (*Oury, Tardieu & Turc, 2016*).

Numerous studies have demonstrated the success of RFS, and complementary irrigation techniques (*Eldoma et al., 2016*; *Ali et al., 2019*). However, further study is required to determine appropriate methods for combining the advantages of RFS planting with supplementary irrigation, and to determine the appropriate planting density. To address these aims, we studied the effects of different maize planting densities and supplementary irrigation treatments on the leaf water use efficiency, Ci, Pn, transpiration rate (Tr), dry matter accumulation, grain yield, and soil water storage under RFS. We elucidated the appropriate timing and amount of supplementary irrigation for maize under RFS, and the appropriate planting density.

MATERIALS AND METHODS

Study site

In 2015 and 2016, field studies were performed at the Dry-Land Agricultural Experimental Station, Pengyang City, Ningxia Province, China, which is located on the Loess Plateau (35°79′N and 106°45′E, altitude of 1,800 m). The annual mean temperature is 8.1 °C. Figure 1 shows the average monthly rainfall in the test area during 2015 and 2016, as well as the 40-year average (1975–2014). Compared with the 40-year average in the growth period for maize, 2015 was a year with normal precipitation, whereas 2016 was a drought year.

Experimental design and field management

This study employed a randomized complete-block design. Three maize planting densities were tested under RFS with four supplementary irrigation treatments at each planting density. The three densities were low density with 52,500 plants ha^{-1}, medium density with 75,000 plants ha^{-1}, which is the conventional density under RFS, and high density with 97,500 plants ha^{-1}. The four supplementary irrigation treatments comprised: NI: no irrigation; IV: 375 m^3 ha^{-1} during 11-leaf stage; IS: 375 m^3 ha^{-1} during the silking stage; and IVS: 375 m^3 ha^{-1}during both stages. The amount of irrigation used in conventional flat cropping is 1,500 m^3 ha^{-1} during the maize growth period in semiarid regions, which is divided into two irrigation applications. Irrigation is applied in the furrows under RFS, and thus irrigation is only placed on the half of planting area, so the irrigation amount was
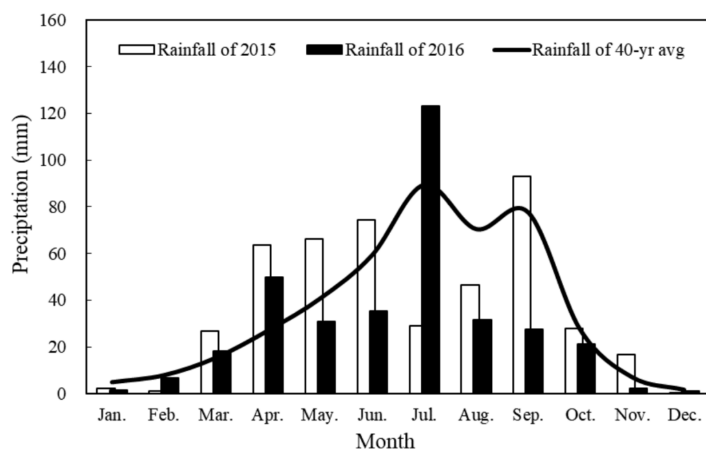
Figure 1 Monthly rainfall distribution in 2015 and 2016, and the 40 year average, at Pengyang Experimental Station, Ningxia Province, China.

Full-size ⬛ DOI: 10.7717/peerj.9959/fig-1

halved to 375 m^3 ha^{-1} per irrigation application. This study tested 12 treatments with three replicates of each. The field area for each plot was 57.6 m^2 (length × width = 12 m × 4.8 m), and a 1.2 m wide isolation zone was set aside to prevent water leaking among the plots. In RFS, the ridges were 60 cm wide and 15 cm high, and covered with plastic (the total width of the plastic film was 0.7 m and the thickness was 0.01 mm; Gansu Tianbao Plastics Co. Ltd, China). The furrows were 60 cm wide and planted with seeds. Maize cultivar "Dafeng 30" is the main variety used locally and it is suitable for planting in semiarid areas where the active accumulated temperature ≥10 °C is above 2,700 °C, and it was sowed on April 23, 2015 and April 21, 2016. Maize was planted by hand, with a line spacing of 60 cm. The plant spacings under the low, medium, and high density treatments were 31.8 cm, 22.2 cm, and 17.1 cm, respectively.

In 2015, the experimental field was deeply plowed. The soil was prepared 10 days before planting maize and the ridges were artificially mulched. The fertilizer application was the same in all treatments, where a base fertilizer containing 150 kg ha^{-1} N and 150 kg ha^{-1} P$_2$O$_5$ was plowed into the topsoil in the furrows, and a topdressing fertilizer with 150 kg ha^{-1} N was applied in the 11-leaf stage. Irrigation in the 11-leaf stage was applied on July 11, 2015 and July 9, 2016, and irrigation was applied during the silking period on July 29, 2015 and July 31, 2016. Weeding and pest control were conducted. Harvesting was performed on October 10, 2015 and October 3, 2016. Maize stalks were removed after harvesting and the plots remained intact until the next year.

Data collection

The soil moisture contents in the 0–200 cm soil layer were measured before sowing and in the three-leaf stage, six-leaf stage, 11-leaf stage, silking stage, filling stage, wax maturity stage, and maturity stage using the soil drilling method. The soil water storage was calculated

as follows (*Jia et al., 2018*):

$$SWS = \sum_{i}^{n} h_i \times \rho_i \times b_i / 10,$$

where *SWS* (mm) is the soil water storage, h_i (cm) is the thickness of a measured soil layer, ρ_i (g cm^{-3}) is the soil bulk density in a measured soil layer, b_i is the soil water content in each soil layer, *n* is the number of soil layers, and $i = 10, 20, 40 \ldots, 200$.

Leaves were sampled randomly from each plot before supplementary irrigation during the 11-leaf stage, after supplementary irrigation during the 11-leaf stage, before supplementary irrigation during the silking stage, after supplementary irrigation during the silking stage, and in the filling stage. The leaf relative water content was calculated as follows (*Afzal, Duiker & Watson, 2017*):

$$RWC = (FW - DW)/(TW - DW) \times 100,$$

where *RWC* is the leaf relative water content, *FM* is the fresh leaf weight, *TM* is the weight of the leaf samples at full turgor, and *DM* is the dry weight of the leaf samples dried in an oven at 60 °C for 24 h (*Jones, 2007*).

Three plants were sampled randomly from each plot before supplementary irrigation during the 11-leaf stage, after supplementary irrigation during the 11-leaf stage, before supplementary irrigation during the silking stage, after supplementary irrigation during the silking stage, and in the filling stage. The leaf photosynthetic characteristics comprising Pn, Tr, C$_i$, and Gs were measured using an LI-6400 portable photosynthesis system analyzer (LI-COR, Lincoln, NE, USA). The ratio of Pn relative to Tr was used as the leaf water use efficiency. Data were recorded between 9:00 and 11:00.

During the maize three-leaf stage, six-leaf stage, 11-leaf stage, silking stage, filling stage, and maturity stage, six maize plants were randomly selected from each plot and dried to constant weight at 70 °C, and the average value was used as the aboveground dry matter content of the maize in each plot. Thirty maize plants were randomly collected from each plot for drying and threshing, before measuring the grain yield, which was adjusted to a moisture content of 13%.

Statistical analysis

The experimental data was analysed with SPSS 13.0 (SPSS Inc., Chicago, IL, USA) and Excel 2010 (Microsoft, USA). The effects of treatments were determined using comparison of means based on the least significant difference test (LSD 0.05).

RESULTS

Soil water storage

During the normal precipitation year (2015), the difference in the soil water storage between the supplementary irrigation treatments was not significant at the sowing, six-leaf, and 11-leaf stages (Fig. 2). During the drought year (2016), the irrigation treatments significantly increased the soil water storage in the sowing, six-leaf and 11-leaf stages mainly due to the accumulated soil moisture because of the application of irrigation in
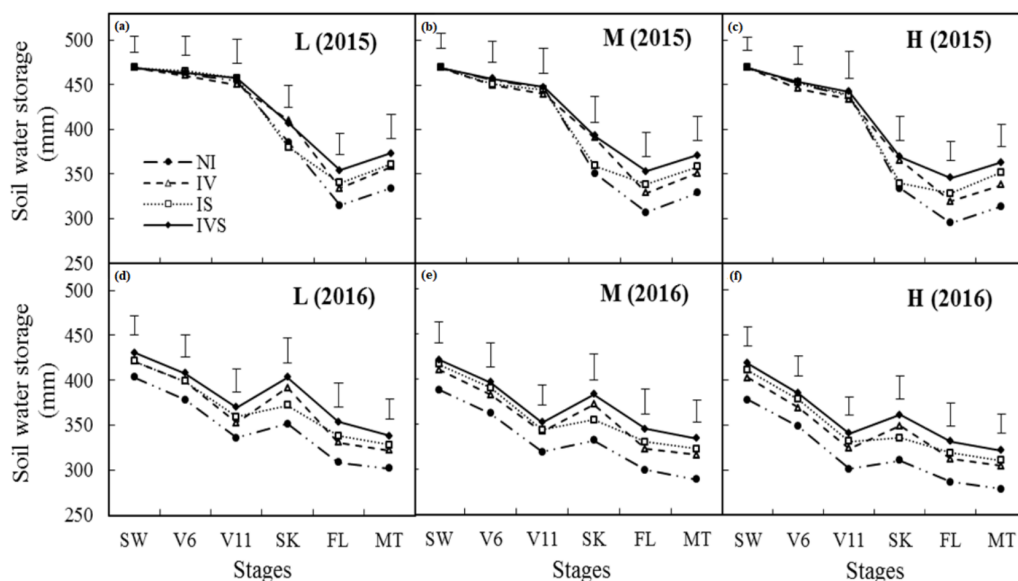
Figure 2 **Variation in soil water storage in the 0–200 cm soil layers at six maize growth stages under different treatments in 2015 and 2016.** L, low planting density (A in 2015 and D in 2016); M, medium planting density (B in 2015 and E in 2016); H, high planting density (C in 2015 and F in 2016); NI, no irrigation; IV, irrigation at the 11-leaf stage; IS, irrigation at the silking stage; IVS, irrigation at the 11-leaf and silking stages. SW, V6, V11, SK, FL and MT means sowing stage, six-leaf stage, 11-leaf stage, silking stage, filling stage, and maturity stages, respectively; Vertical bars represent the LSD values at $p = 0.05$ level.

Full-size 🖼 DOI: 10.7717/peerj.9959/fig-2

2015. The soil water storage levels were significantly higher in IV and IVS than NI during the silking stage in both years. Compared with the NI treatment, supplementary irrigation during the silking period significantly increased the soil water storage during the filling and maturity stages. We also found that the differences in the soil water storage under all three planting densities were small during the sowing, six-leaf, and 11-leaf stages in both years, but the soil water storage decreased significantly as the planting density increased during the silking, filling, and maturity stages, especially in the drought year (2016). Thus, the strong growth of maize after silking led to the consumption of a large amount of soil moisture in the high planting density treatment. The results also indicated a high level of intraspecific competitive pressure, which would be detrimental to the growth of maize during the late growth period.

Leaf relative water content

Prior to the 11-leaf stage irrigation application in 2015, there were no significant differences in the leaf relative water contents among the different irrigation levels at the same planting density (Fig. 3). However, the leaf relative water contents were significantly higher in IV and IVS than NI after the 11-leaf stage irrigation application during both years, thereby indicating that irrigating in the 11-leaf stage provided good water conditions for the vegetative growth of maize and it significantly increased the leaf relative water content.

In 2015, due to the lower rainfall from the 11-leaf stage to the silking stage, the leaf relative water contents were lower in all treatments. In 2016, two heavy rainfall events
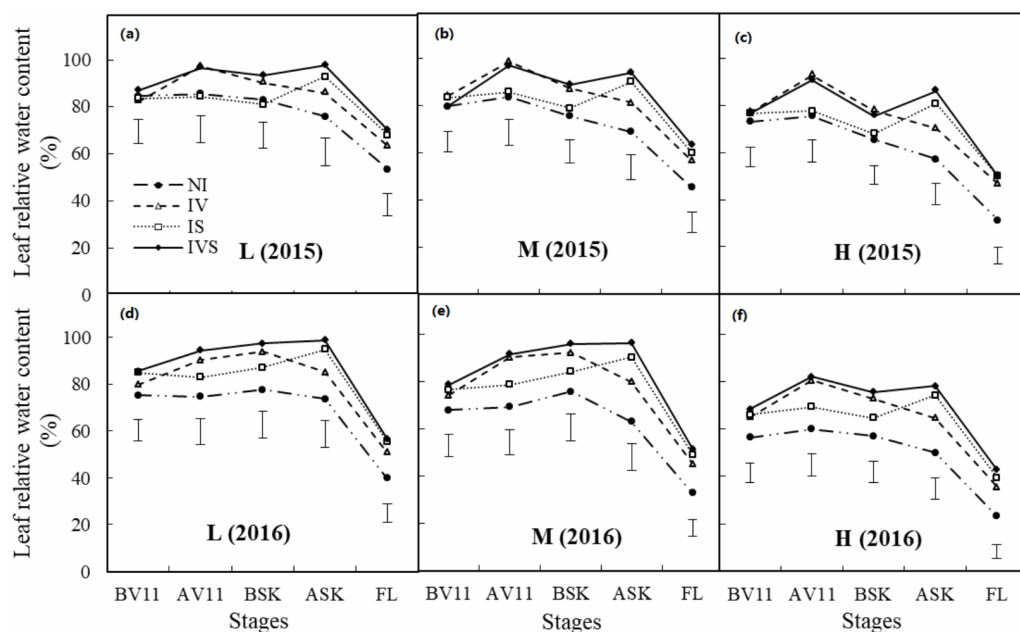
Figure 3 **Effects of deficient treatments on leaf relative water content of maize in 2015 and 2016.** L, low planting density (A in 2015 and D in 2016); M, medium planting density (B in 2015 and E in 2016); H, high planting density (C in 2015 and F in 2016); NI, no irrigation; IV, irrigation at the 11-leaf stage; IS, irrigation at the silking stage; IVS, irrigation at the 11-leaf and silking stages; BV11, AV11, BSK, ASK and FL means before supplementary irrigation at 11-leaf stage, after supplementary irrigation at 11-leaf stage, before supplementary irrigation at silking stage, after supplementary irrigation at silking stage, and supplementary irrigation at filling stage, respectively; Vertical bars represent LSD values ($P < 0.05$).

Full-size ⬚ DOI: 10.7717/peerj.9959/fig-3

occurred between the 11-leaf stage and the silking stage, which increased the leaf relative water contents in all treatments at the low and medium planting densities. After irrigation during the silking stage, the leaf relative water contents were significantly higher under IS and IVS in both years compared with NI, and this was also the case during the filling period. Under the same irrigation mode, the leaf relative water content was significantly lower with the high planting density than the low and medium densities.

These results indicate that the leaf relative water contents were closely related to rainfall and soil moisture. Sufficient precipitation or irrigation increased the soil water storage, thereby increasing the leaf relative water content. Irrigating during the silking period increased the leaf relative water content in the filling stage, which was beneficial for filling the maize grains. However, the leaf relative water content was significantly lower under the high planting density treatment due to the greater intraspecific competitive pressure.

Stomatal conductance (Gs) and intercellular CO_2 concentration (C_i)

Prior to irrigation in the 11-leaf stage during 2015, there were no significant differences in Gs, whereas Gs was significantly higher under IVS in 2016 compared with NI (Fig. 4). Gs was significantly higher under IV and IVS compared with NI after irrigation in the 11-leaf stage during both years, and Gs was significantly lower under the high planting density treatment. In 2015, prior to irrigation during the silking stage, Gs decreased in
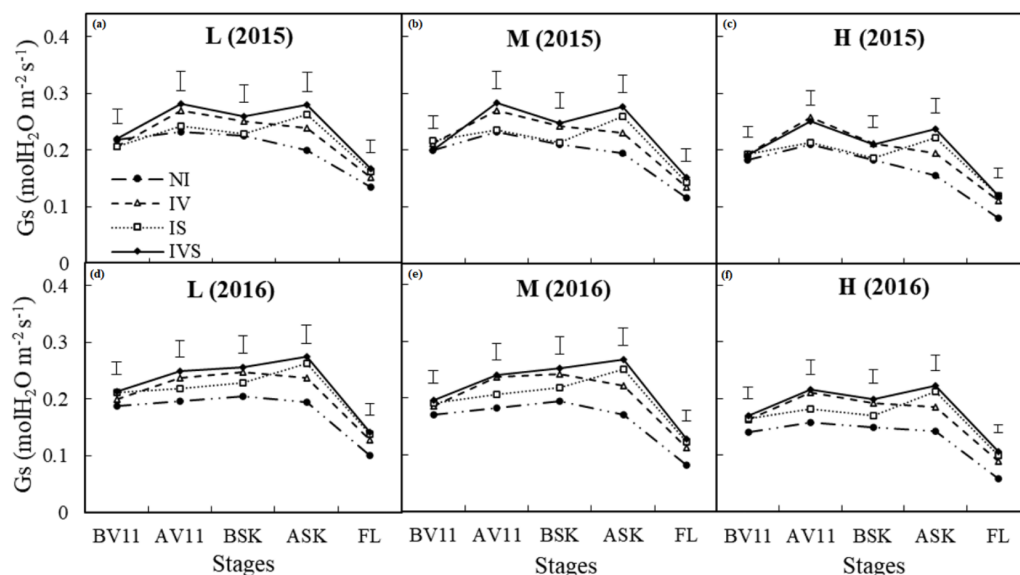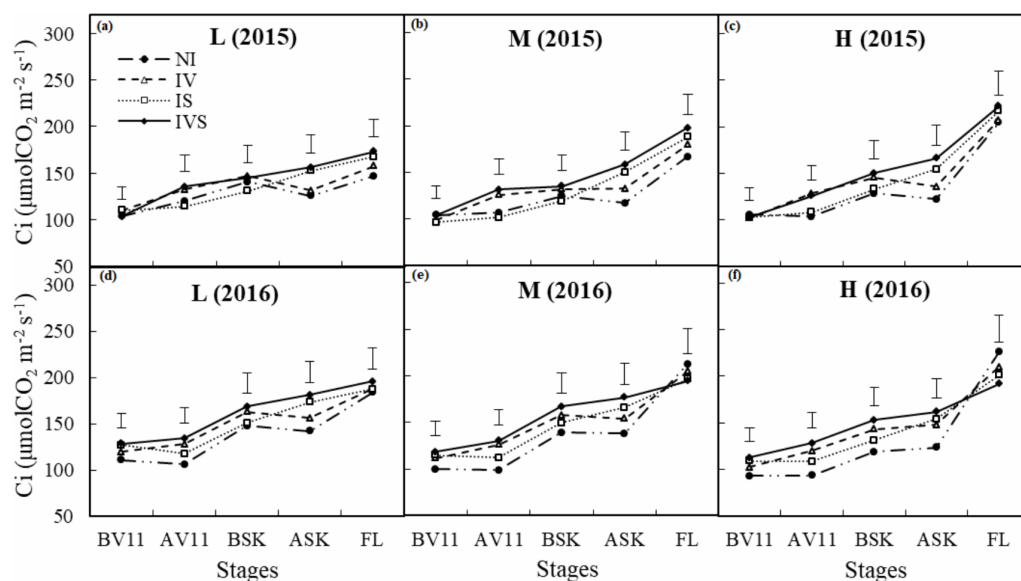
Figure 4 **Effects of deficient treatments on stomatal conductance (Gs) of maize leaves in 2015 and 2016.** L, low planting density (A in 2015 and D in 2016); M, medium planting density (B in 2015 and E in 2016); H, high planting density (C in 2015 and F in 2016); NI, no irrigation; IV, irrigation at the 11-leaf stage; IS, irrigation at the silking stage; IVS, irrigation at the 11-leaf and silking stages; BV11, AV11, BSK, ASK and FL means before supplementary irrigation at 11-leaf stage, after supplementary irrigation at 11-leaf stage, before supplementary irrigation at silking stage, after supplementary irrigation at silking stage, and supplementary irrigation at filling stage, respectively; Vertical bars represent LSD values ($P < 0.05$).

Full-size ☑ DOI: 10.7717/peerj.9959/fig-4

each treatment due to the lower precipitation from the 11-leaf stage to the silking stage. After supplementary irrigation during the silking stage in both years, Gs was significantly higher under IS and IVS than NI, and Gs was significantly higher with the low and medium planting density treatments than the high density treatment until the filling stage. These results demonstrate that sufficient rainfall or irrigation could increase the leaf Gs, which is beneficial to leaf gas exchange and photosynthesis. However, a high planting density significantly reduced Gs in the maize leaves, which is not conducive to gas exchange during the reproductive growth stage.

Prior to irrigation during the 11-leaf stage, the differences in C_i were not significant in 2015, whereas C_i was significantly higher under IVS than NI in 2016 (Fig. 5). After irrigation during the 11-leaf stage and silking stage, C_i was significantly higher under IV and IVS compared with NI in both years. These results demonstrate that supplementary irrigation could significantly increase C_i. In the drought year (2016), plants were severely affected by drought stress in the high planting density treatment, thereby resulting in a decrease in C_i, whereas C_i was affected less by the planting density in the normal year (2015). From the silking stage to the filling stage, C_i increased as Gs decreased in both years (Figs. 4 and 5). In 2015, C_i was significantly higher under IS and IVS during the filling period compared with NI at the low and medium planting densities. However, C_i was significantly higher under NI than IVS at the high planting density in 2016. During the filling stage, C_i was significantly higher at the high planting density in both years compared

Figure 5 Effects of deficient treatments on intercellular CO$_2$ concentration (Ci) of maize leaves in 2015 and 2016. L, low planting density (A in 2015 and D in 2016); M, medium planting density (B in 2015 and E in 2016); H, high planting density (C in 2015 and F in 2016); NI, no irrigation; IV, irrigation at the 11-leaf stage; IS, irrigation at the silking stage; IVS, irrigation at the 11-leaf and silking stages; BV11, AV11, BSK, ASK and FL means before supplementary irrigation at 11-leaf stage, after supplementary irrigation at 11-leaf stage, before supplementary irrigation at silking stage, after supplementary irrigation at silking stage, and supplementary irrigation at filling stage, respectively; Vertical bars represent LSD values ($P < 0.05$).

Full-size ◰ DOI: 10.7717/peerj.9959/fig-5

with the low planting density treatment with the same irrigation mode. These results may be explained by the low soil moisture damaging the leaves, thereby leading to increases in C$_i$ during the filling period, especially with the high planting density in the drought year without any irrigation treatment.

Net photosynthetic rate (Pn) and transpiration rate (Tr)

Two-way analysis of variance showed (Table 1) that prior to supplementary irrigation in the 11-leaf stage, the planting density and irrigation mode had no significant effects on Pn in 2015 ($P > 0.05$), but they had significant effects in 2016 ($P < 0.01$). After supplementary irrigation during the 11-leaf stage, the effects of the planting density and irrigation mode on Pn were significant or highly significant in both years ($P < 0.05$ or $P < 0.01$). Compared with the mean value, the results showed that Pn decreased significantly as the planting density increased in 2016 prior to supplementary irrigation in the 11-leaf stage, whereas it increased with supplementary irrigation treatment.

The average Pn was significantly higher with the low planting density treatment in both years compared with the high planting density from the 11-leaf stage to the silking stage, and the average Pn was significantly higher under IV and IVS than NI in 2016. After irrigation during the silking and filling stages, the average Pn was significantly higher with the low and medium planting densities in both years compared with the high planting density treatment, and Pn was significantly higher under IS and IVS than NI. These results

Peer J

Table 1 **Effects of experimental treatments on the net photosynthetic rate of maize leaves (Pn, μmol CO$_2$ m^{-2} s^{-1}) in 2015–2016.** Abbreviations for different treatments are defined in Fig. 3. Values followed by different letters within a column are significantly different at the 5% probability level (least significant difference; $n = 3$).

Years	Planting densities	Irrigation modes	Before irrigation at 11-leaf stage	After irrigation at 11-leaf stage	Before irrigation at silking stage	After irrigation at silking stage	Filling stage
2015	L	NI	22.5a	24.9abc	25.7ab	26.6bcd	19.8c
		IV	23.2a	28.0a	27.2a	28.2abc	22.3ab
		IS	23.2a	24.8abc	26.0ab	31.4a	23.8a
		IVS	22.8a	28.1a	27.6a	31.9a	24.0a
	M	NI	22.5a	23.5bc	24.7abc	25.2cd	18.1cd
		IV	22.7a	27.4a	26.2ab	27.1bcd	20.2bc
		IS	23.0a	23.8bc	24.7abc	30.0ab	22.6ab
		IVS	22.5a	27.8a	26.4ab	30.0ab	22.9a
	H	NI	21.9a	22.4c	21.5c	21.1e	14.4e
		IV	21.9a	25.8ab	23.0bc	23.6de	16.5de
		IS	22.7a	22.5c	21.3c	25.7cd	18.6cd
		IVS	21.8a	26.1ab	23.2bc	26.1bcd	18.6cd
	Average	L	22.9A	26.4A	26.6A	29.5A	22.5A
		M	22.7A	25.6AB	25.5A	28.0A	20.9B
		H	22.1A	24.2B	22.2B	24.1B	17.0C
		NI	22.3A	23.6B	24.0A	24.3B	17.4C
		IV	22.6A	27.0A	25.5A	26.3B	19.7B
		IS	23.0A	23.7B	24.0A	29.0A	21.7A
		IVS	22.4A	27.3A	25.7A	29.3A	21.9A
	ANOVA	PD	ns	*	**	**	**
		IM	ns	**	ns	**	**
		PD × IM	ns	ns	ns	ns	ns
	L	NI	21.4abc	22.7cde	23.3cd	23.5def	15.2de
		IV	22.7a	26.6a	26.9ab	27.2bcd	17.8bc
		IS	23.1a	24.8abc	25.2abc	29.6ab	19.5ab
		IVS	23.3a	26.7a	27.1a	31.3a	19.9a
	M	NI	19.3bcd	20.6de	21.0def	21.3fg	13.7ef
		IV	21.1abc	25.0abc	25.6abc	25.8de	16.6cd
		IS	21.8ab	23.6abcd	23.9bcd	28.6abc	17.3c
		IVS	22.5a	26.0ab	25.8abc	29.8ab	17.8bc
		NI	16.4e	17.7f	18.2f	18.7 g	9.2 g

Table 1 (*continued*)

Years	Planting densities	Irrigation modes	Before irrigation at 11-leaf stage	After irrigation at 11-leaf stage	Before irrigation at silking stage	After irrigation at silking stage	Filling stage
2016	H	IV	18.4de	22.6cde	21.8de	22.3ef	12.3f
		IS	18.8cde	20.2ef	20.1ef	25.8de	13.3ef
		IVS	19.4bcd	23.0bcde	22.0de	26.5cd	14.6de
	Average	L	22.6A	25.2A	25.6A	27.9A	18.1A
		M	21.2B	23.8A	24.1B	26.4A	16.3B
		H	18.2C	20.9B	20.5C	23.3B	12.4C
		NI	19.0B	20.3C	20.8C	21.2C	12.7C
		IV	20.7A	24.7A	24.8A	25.1B	15.6B
		IS	21.2A	22.9B	23.0B	28.0A	16.7AB
		IVS	21.7A	25.2A	25.0A	29.2A	17.4A
	ANOVA	PD	**	**	**	**	**
		IM	**	**	**	**	**
		PD × IM	ns	ns	ns	ns	ns

Notes.

ANOVA, analysis of variance

[**] significance at 1% probability level

[*] significance at 5% probability level

ns, not significant; IM, irrigation mode; PD, planting density.

Lowercase and uppercase letters in columns indicate significant differences among planting density and irrigation mode treatments, respectively.

indicate that the high planting density significantly reduced Pn during the maize silking and filling stages, which was not conducive to the reproductive growth of maize. Irrigating during the silking period provided water for the later growth of the maize, which was beneficial for photosynthesis during the filling stage.

The average Tr was significantly higher with the low and medium planting densities than the high planting density during the 11-leaf stage in both years (Table 2). The average Tr was significantly higher under IV and IVS than IS after irrigation during the 11-leaf stage in both years. During the silking stage, the average Tr was significantly higher with the low and medium planting densities than the high planting density in both years. After irrigation during the silking stage, the average Tr was significantly higher under IS and IVS than NI and IV. These results demonstrate that the planting density had a great influence on Tr prior to irrigation, and the high planting density significantly reduced Tr, whereas the supplementary irrigation treatments could significantly increase Tr. Comparing the average values showed that Tr was significantly higher with the low and medium planting densities than the high planting density during the filling period in both years, and the average Tr was significantly higher under IS and IVS than NI.

Leaf water use efficiency

Prior to supplementary irrigation during the 11-leaf stage, the leaf water use efficiency in both years was mainly affected by the planting density, where the leaf water use efficiency was significantly higher with the low and medium planting densities than the high planting density (Table 3). After supplementary irrigation during the 11-leaf stage, the leaf water use efficiency was mainly affected by the supplementary irrigation mode. The leaf water use efficiency was significantly higher under IS than IV and IVS because irrigation during the 11-leaf period significantly increased Tr, thereby decreasing the leaf water use efficiency. Similar findings were obtained during the silking period. During the filling period, compared with the high planting density, the average leaf water use efficiency in 2015 increased by 12.5% and 9.2% under the low and medium planting densities, respectively, and by 7.7% and 5.0% in 2016. Compared with NI, the IV, IS, and IVS treatments increased the average leaf water use efficiency in 2015 by 9.3%, 19.4%, and 18.3%, respectively, and by 7.5%, 12.3%, and 12.6% in 2016.

These results indicate that severe water stress was experienced with the high planting density during the filling stage and Pn decreased in the leaves to significantly reduce the leaf water use efficiency. Supplementary irrigation during the silking stage provided favorable water conditions for filling the maize grains and, increasing the leaf Pn, which resulted in a significant increase in the leaf water use efficiency.

Total dry matter accumulation and grain yield

In 2015 and 2016, the total dry matter accumulation increased significantly as the planting density increased (Table 4). Compared with NI, the average total dry matter accumulation in 2015 under IV, IS, and IVS increased by 7.6%, 3.3%, and 7.5%, respectively, and by 14.7%, 12.9%, and 17.4% in 2016. These results indicate that supplementary irrigation during the 11-leaf stage could increase the total dry matter accumulation, and the total

Table 2 Effects of experimental treatments on the transpiration rate of maize leaves (Tr, mmol H_2O m^{-2} s^{-1}) in 2015–2016. Abbreviations for different treatments are defined in Fig. 3. Values followed by different letters within a column are significantly different at the 5% probability level (least significant difference; $n = 3$).

Years	Planting densities	Irrigation modes	Before irrigation at 11-leaf stage	After irrigation at 11-leaf stage	Before irrigation at silking stage	After irrigation at silking stage	Filling stage
2015		NI	4.97abc	5.25b	4.64ab	4.72cde	4.07abc
	L	IV	5.21a	6.70a	4.89a	4.98cde	4.27ab
		IS	5.14ab	5.43b	4.63ab	6.07a	4.28ab
		IVS	5.15ab	6.72a	4.84ab	6.15a	4.37a
		NI	4.70abcd	5.12b	4.55ab	4.57de	4.00abcd
	M	IV	4.73abcd	6.63a	4.73ab	4.86cde	4.06abc
		IS	4.75abcd	5.20b	4.53ab	5.88ab	4.10abc
		IVS	4.79abcd	6.51a	4.75ab	5.96ab	4.15abc
		NI	4.35cd	5.02b	4.26ab	4.25e	3.47d
	H	IV	4.30d	6.23a	4.28ab	4.37e	3.61cd
		IS	4.51cd	5.11b	4.22b	5.26bcd	3.65cd
		IVS	4.45cd	6.33a	4.35ab	5.41bc	3.74bcd
	Average	L	5.12A	6.02A	4.75A	5.48A	4.25A
		M	4.74B	5.87A	4.64A	5.32A	4.08A
		H	4.40C	5.67A	4.28B	4.82B	3.62B
		NI	4.67A	5.13B	4.48A	4.51B	3.85B
		IV	4.75A	6.52A	4.63A	4.74B	3.98A B
		IS	4.80A	5.25B	4.46A	5.74A	4.01A
		IVS	4.80A	6.52A	4.65A	5.84A	4.08A
	ANOVA	PD	**	ns	**	**	**
		IM	ns	**	ns	**	*
		PD × IM	ns	ns	ns	ns	ns
		NI	4.23abcd	4.61de	4.04cd	4.31ef	3.33cde
	L	IV	4.36a	6.17a	4.95a	4.75cde	3.62abc
		IS	4.39a	4.90cd	4.20bcd	5.96a	3.86ab
		IVS	4.43a	6.12a	5.01a	6.11a	3.95a
		NI	4.02abcd	4.45de	4.03cd	4.18ef	3.11de
	M	IV	4.22abcd	5.87ab	4.69ab	4.48def	3.48bcd
		IS	4.18abcd	4.69cde	4.05cd	5.61ab	3.47bcde
		IVS	4.26abc	5.95ab	4.77ab	5.83ab	3.54abc
		NI	3.70d	4.05e	3.68d	3.78f	2.19f

Table 2 (*continued*)

Years	Planting densities	Irrigation modes	Before irrigation at 11-leaf stage	After irrigation at 11-leaf stage	Before irrigation at silking stage	After irrigation at silking stage	Filling stage
2016	H	IV	3.89bcd	5.33bc	4.19bcd	4.14ef	2.75e
		IS	3.74cd	4.35de	3.72d	5.12bcd	2.78e
		IVS	3.83bcd	5.38bc	4.17cd	5.28bc	3.04de
	Average	L	4.35A	5.45A	4.55A	5.22A	3.69A
		M	4.17A	5.24A	4.36A	5.02A	3.40B
		H	3.79B	4.78B	3.94B	4.58B	2.69C
		NI	3.99A	4.37B	3.92B	4.09B	2.88B
		IV	4.15A	5.79A	4.58A	4.46B	3.28A
		IS	4.10A	4.65B	3.99B	5.48A	3.37A
		IVS	4.17A	5.82A	4.65A	5.74A	3.51A
	ANOVA	PD	**	**	**	**	**
		IM	ns	**	**	**	**
		PD × IM	ns	ns	ns	ns	ns

Notes.

ANOVA, analysis of variance

[**] significance at 1% probability level

[*] significance at 5% probability level; ns: not significant

IM, irrigation mode; PD, planting density.

Lowercase and uppercase letters in columns indicate significant differences among planting density and irrigation mode treatments, respectively.

Table 3 Effects of experimental treatments on the water use efficiency of maize leaves (WUE$_L$, μmol CO$_2$ mmol H$_2$O^{-1}) in 2015–2016. Abbreviations for different treatments are defined in Fig. 3. Values followed by different letters within a column are significantly different at the 5% probability level (least significant difference; $n =$ 3).

Years	Planting densities	Irrigation modes	Before irrigation at 11-leaf stage	After irrigation at 11-leaf stage	Before irrigation at silking stage	After irrigation at silking stage	Filling stage
2015		NI	4.53ab	4.73a	5.54a	5.62a	4.86abc
	L	IV	4.44ab	4.17ab	5.56a	5.66a	5.24ab
		IS	4.52ab	4.56ab	5.62a	5.16ab	5.56a
		IVS	4.43b	4.18ab	5.69a	5.18ab	5.49a
		NI	4.80ab	4.59ab	5.43a	5.51ab	4.51cd
	M	IV	4.80ab	4.13b	5.54a	5.57ab	4.98abc
		IS	4.84ab	4.58ab	5.44a	5.10ab	5.51a
		IVS	4.70ab	4.26ab	5.55a	5.04ab	5.53a
		NI	5.04ab	4.46ab	5.05a	4.96ab	4.16d
	H	IV	5.10a	4.13b	5.37a	5.40ab	4.57bcd
		IS	5.04ab	4.40ab	5.06a	4.88ab	5.01bc
		IVS	4.89ab	4.12b	5.32a	4.82b	4.99bc
Average	L		4.48B	4.41A	5.60A	5.41A	5.29A
	M		4.78A	4.39A	5.49AB	5.30AB	5.13A
	H		5.02A	4.28A	5.20B	5.01B	4.70B
		NI	4.79A	4.59A	5.34A	5.36AB	4.51C
		IV	4.78A	4.15B	5.49A	5.54A	4.93B
		IS	4.80A	4.51A	5.37A	5.05B	5.39A
		IVS	4.67A	4.19B	5.52A	5.01B	5.34A
ANOVA		PD	**	ns	*	ns	**
		IM	ns	**	ns	*	**
		PD $\times$ IM	ns	ns	ns	ns	ns
		NI	5.06ab	4.91ab	5.76ab	5.46a	4.57ab
	L	IV	5.23a	4.31bc	5.43abc	5.73a	4.92a
		IS	5.26a	5.07a	5.99a	5.19a	5.04a
		IVS	5.25a	4.37bc	5.42abc	5.11a	5.03a
		NI	4.80ab	4.64abc	5.21bc	5.09a	4.42ab
	M	IV	5.01ab	4.27c	5.57abc	5.76a	4.77ab
		IS	5.23a	5.03a	5.89ab	5.10a	4.99a
		IVS	5.28a	4.36bc	5.41abc	5.11a	5.02a
		NI	4.41b	4.36bc	4.96c	4.94a	4.20b

Table 3 (*continued*)

Years	Planting densities	Irrigation modes	Before irrigation at 11-leaf stage	After irrigation at 11-leaf stage	Before irrigation at silking stage	After irrigation at silking stage	Filling stage
2016	H	IV	4.71ab	4.23c	5.21bc	5.38a	4.49ab
		IS	5.02ab	4.65abc	5.41abc	5.04a	4.78ab
		IVS	5.07ab	4.28c	5.27abc	5.02a	4.80ab
	Average	L	5.20A	4.66A	5.65A	5.37A	4.89A
		M	5.08AB	4.57A	5.52AB	5.26A	4.80AB
		H	4.80C	4.38A	5.21B	5.09A	4.57B
		NI	4.76B	4.64AB	5.31B	5.16B	4.40B
		IV	4.98AB	4.27C	5.40AB	5.62A	4.73A
		IS	5.17A	4.91A	5.76A	5.11B	4.94A
		IVS	5.20A	4.34BC	5.36AB	5.08B	4.95A
	ANOVA	PD	*	ns	*	ns	*
		IM	*	**	*	*	**
		PD × IM	ns	ns	ns	ns	ns

Notes.

ANOVA, analysis of variance

** significance at 1% probability level

* significance at 5% probability level

ns, not significant; IM, irrigation mode; PD, planting density.

Lowercase and uppercase letters in columns indicate significant differences among planting density and irrigation mode treatments, respectively.

dry matter accumulated in the drought year (2016) was higher than that in the normal year (2015). This effect was particularly significant in the drought year with medium and high planting densities, and during the post-silking period. The average total dry matter accumulation increased significantly as the planting density increased during the entire growing period in both years. In addition, irrigating during the silking period increased the total dry matter accumulation compared with IS and IVS during the entire growth period, and the increase was higher in the drought year than the normal year.

The average grain yields in 2015 increased by 8.8% and 9.7% with the medium and high planting densities, respectively, compared with the low planting density, and similar increases of 10.2% and 8.2% were obtained in 2016. These results demonstrate that the medium and high planting densities significantly increased the grain yield, whereas the high planting density did not significantly increase the grain yield compared with the medium planting density and it even decreased the grain yield in the drought year (2016). The average grain yields in 2015 increased by 8.9%, 13.7%, and 15.2% under IV, IS, and IVS, respectively, compared with NI, and by 18.3%, 30.3%, and 31.4% in 2016. These results indicate that supplementary irrigation could significantly increase the grain yield in maize. The effect of supplementary irrigation was greater during the silking stage than the 11-leaf stage. Applying supplementary irrigation twice did not significantly increase the grain yield compared with only applying irrigation during the silking stage.

DISCUSSION

Soil water content

In semiarid regions of China, crop production is severely limited by water shortages, particularly due to the mismatch between rainfall and crop water demands, and severe water shortages during the reproductive growth stage of maize (*Wang et al., 2009*). RFS increases the amount of rainfall infiltration and soil water storage by collecting rainfall in furrows (*Ren, Jia & Chen, 2008*). In the present study, we found that supplementary irrigation did not significantly increase the soil water storage prior to the silking stage in the normal year (2015), whereas it significantly increased the soil water storage in the drought year (2016) due to the lower precipitation and accumulation of water from the previous year. In addition, although the amount of irrigation used under IVS was twice that under IS, the soil water storage did not differ significantly between the two treatments. Our research area was affected by strong sunlight and strong winds, and the annual water surface evaporation was about 1,700 mm. Thus, soil water evaporation was the main cause of water losses (*Feng et al., 2016*; *Kang et al., 2003*). However, due to the limited amount of water applied in the irrigation treatment, the soil water storage did not differ significantly among the supplementary irrigation treatments.

We also found that the soil water storage did not decrease as the planting density increased before the silking stage, probably because the plants were small in this stage and the water loss was mainly caused by soil evaporation. In addition, the high planting density provided a benefit due to shading (*Li et al., 2016*), which reduced the sunlight reaching the surface, thereby inhibiting soil water evaporation. However, after the silking stage, the

Table 4 Effects of experimental treatments on the total dry matter accumulation (TDMA, t ha⁻¹) and gain yield (t ha⁻¹) in 2015–2016. Abbreviations for different treatments are defined in Fig. 3). Values followed by different letters within a column are significantly different at the 5% probability level (least significant difference; $n = 3$).

Years	Planting densities	Irrigation patterns	Pre-silking TDMA	Post-silking TDMA	Entire growth period TDMA	Grain yield
2015		NI	11.3f	11.5d	22.8e	10.9c
	L	IV	11.9ef	12.4cd	24.3de	11.9bc
		IS	11.4f	13.7abc	25.1cd	12.3ab
		IVS	11.9ef	13.3abc	25.2cd	12.4ab
		NI	13.6de	13.1bcd	26.7bcd	11.5bc
	M	IV	14.7bcd	13.2bcd	27.9abcd	12.6ab
		IS	14.0cd	14.8ab	28.8abc	13.4a
		IVS	14.7bcd	14.5ab	29.2ab	13.5a
		NI	15.5abc	14.5ab	30.0ab	11.8bc
	H	IV	16.8a	14.5ab	31.4a	12.7ab
		IS	16.3ab	15.3a	31.6a	13.4a
		IVS	16.8a	15.0ab	31.8a	13.6a
	Average	L	11.6C	12.7C	24.4C	11.7B
		M	14.3B	13.9B	28.1B	12.8A
		H	16.4A	14.8A	31.2A	12.9A
		NI	13.5A	13.0C	26.5B	11.4C
		IV	14.5A	13.4BC	27.9AB	12.4B
		IS	13.9A	14.6A	28.5A	12.9A
		IVS	14.5A	14.2AB	28.7A	13.1A
	ANOVA	PD	**	**	**	**
		IM	ns	*	*	**
		PD × IM	ns	ns	ns	ns
	L	NI	10.0d	11.0e	21.0f	9.2c
		IV	11.4d	12.0cde	23.4def	11.1b
		IS	11.1d	13.4abc	24.5cde	11.3b
		IVS	11.6d	13.0abcd	24.7cde	11.4b
	M	NI	11.4d	10.8e	22.2ef	9.8c
		IV	13.4c	12.3bcd	25.7bcde	11.5b
		IS	13.3c	13.9ab	27.1abc	13.0a
		IVS	13.7bc	13.0abcd	26.7abcd	13.1a
		NI	13.6bc	11.4de	25.0cde	9.6c

Table 4 (*continued*)

Years	Planting densities	Irrigation patterns	Pre-silking TDMA	Post-silking TDMA	Entire growth period TDMA	Grain yield
2016	H	IV	15.3a	13.6abc	29.0ab	11.2b
		IS	15.1ab	14.7a	29.8a	12.8a
		IVS	15.7a	14.2a	29.9a	12.9a
	Average	L	11.0C	12.4B	23.4C	10.8B
		M	12.9B	12.5B	25.4B	11.9A
		H	14.9A	13.5A	28.4A	11.6A
		NI	11.7B	11.1C	22.7B	9.5C
		IV	13.4A	12.7B	26.0A	11.3B
		IS	13.2A	14.0A	27.1A	12.4A
		IVS	13.7A	13.5AB	27.1A	12.5A
	ANOVA	PD	**	*	**	**
		IM	**	**	**	**
		PD × IM	ns	ns	ns	ns

Notes.

ANOVA, analysis of variance

** significance at 1% probability level

*significance at 5% probability level; ns: not significant

IM, irrigation mode; PD, planting density.

Lowercase and uppercase letters in columns indicate significant differences among planting density and irrigation mode treatments, respectively.

soil water storage decreased significantly with the high planting density due to the higher consumption of water for plant growth, which was disadvantageous to maize development in the later growth stages.

Photosynthesis characteristics of maize leaves

Water stress can disrupt the condition of plants, which can regulate their metabolic and defense systems to adapt to the environment. It has been reported that the relative water content of maize leaves in the seedling stage decreased by 19.8% compared with the control after 6 days of water deficit (*Nikolaeva, Maevskaya & Voronin, 2017*). Studies have also shown that subjecting plants to severe water stress when the leaf relative water content was below 70% (*Ennahli & Earl, 2005*) could damage the photosynthetic organs in the leaves (*Souza et al., 2004*). The results obtained in our two-year field trial showed that the relative water content of the maize ear leaves was less than 70% during the filling stage under NI. In addition, the relative water contents were below 40% with the medium and high planting densities, which may damage the photosynthetic organs in the leaves. In both the normal year and drought year, irrigation significantly improved the leaf relative water content, especially when the irrigation was applied during the silking period, which was beneficial for photosynthesis in the maize leaves.

Pn can reflect the photosynthetic efficiency of plants. Previous studies have shown that Pn and Tr decreased in the leaves as the soil water content reduced (*Rouhi et al., 2007*). Similar results were found in our study. The soil water storage differed little before irrigation during the 11-leaf stage in 2015, and thus Pn did not differ significantly (Fig. 2). However, due to the accumulation of soil moisture during 2015, the supplementary irrigation treatment increased the soil water storage during the 11-leaf stage in 2016, which increased Pn, and supplementary irrigation during the silking period further increased Pn. Many studies have shown that water deficit can inhibit the photosynthetic rate in plants, mainly due to the increased stomatal resistance under drought stress limiting the diffusion of CO_2 from the air into the leaves (*Lawlor, 2002*; *Lavinsky et al., 2015*). Water stress can limit photosynthesis due to stomatal or non-stomatal factors (*Medrano et al., 2002*; *Flexas et al., 2006*). According to *Farquhar & Sharkey (1982)*, the decrease in Pn can be explained by an increase in stomatal resistance when Gs and C_i decrease simultaneously, but if Pn decreases as C_i increases, it is considered that the main limiting factor for Pn is the decreased photosynthetic activity of mesophyll cells.

Our results showed that Gs and C_i were lower under NI than the supplementary irrigation treatments, and Pn was also significantly lower after irrigation during the 11-leaf stage and silking stage. These results indicated that water stress increased the stomatal resistance of the leaves under NI, which reduced Gs and C_i, thereby decreasing Tr and Pn during the 11-leaf stage and silking stage. However, *Vitale et al. (2009)* showed that maize can effectively resist drought during the vegetative growth stage and the leaf photosynthetic capacity was not affected by water stress, which appears to contradict our findings, although this disparity may be explained by differences in the degree of drought stress or the maize development stages considered.

Carvalho, Cunha & Silva (2011) found that C_i decreased in the early stages under water stress but increased under higher water stress. *Vu et al. (1998)* indicated that the RuBisCO enzyme content and activity decreased in the leaves under severe water stress conditions, which weakened the Calvin cycle and increased C_i in the sheath cells. *Azizian & Sepaskhah (2014)* found that leaf aging reduced Pn and Gs during the later growth stages in maize. According to *Vitale et al. (2007)*, leaf gas exchange was restricted by Gs under water stress conditions, thereby leading to a decrease in Pn, but Pn increased significantly after irrigation. Our results are similar to those obtained in these previous studies. We also found that NI significantly decreased Gs, Tr, and Pn during the filling stage at the high planting density in the drought year (2016), whereas C_i increased. This was due to the low soil moisture content during the filling period in the drought year, which was particularly harsh with a high planting density, and this led to leaf aging and caused a decrease in Pn due to non-stomatal factors.

Dry matter accumulation and grain yield

A previous study conducted by *Fan et al. (2014)* in the semiarid area of northwestern China showed that maize was more sensitive to water availability during the silking stage than the large bell stage. In the Yellow River irrigation area of Ningxia, China, *Liu et al. (2012)*, found that the maize yields were significantly reduced by drought stress during the silking stage, which shortened the duration of the grain filling stage. By contrast, supplementary irrigation during the silking period was conducive to the accumulation of dry matter during later development and it significantly increased the grain yields. Our results also showed that supplementary irrigation significantly increased the total dry matter accumulation and grain yields compared with the un-irrigated control, but the effects of applying supplementary irrigation twice and only irrigating during silking stage did not differ.

Zhang et al. (2005) showed that when the planting density was excessively high, maize plants competed for nutrients, light, and water, thereby resulting in insufficient grain filling during the later growth stages, with reductions in the 100-grain weight, dry matter accumulation, and yields. *Dou, Yu & Yu (2013)* found that a medium planting density (60,000 plants to 68,000 plants ha^{-1}) with supplementary irrigation improved the water consumption by maize, thereby increasing the maize dry matter accumulation and grain yield. We obtained similar results where the total dry matter accumulation increased significantly with the planting density prior to the silking stage over two years, but the total dry matter accumulation increased slowly as the planting density increased after the silking stage. These results can be explained by the low rainfall after silking and the competitive pressure increasing under high density maize planting to cause significant decreases in the leaf area index and photosynthetic rate during the filling stage. The restricted accumulation of dry matter after the silking stage under high density planting then affected grain development and the yield, especially under the conditions with no irrigation. *Farnham (2001)* reported that the increase in the grain yield was not significant when the maize planting density was increased from 59,000 plants ha^{-1} to 89,000 plants ha^{-1}. Many studies have shown that an excessive planting density reduces the availability of growth factors such

as light, heat, and moisture (*Widdicombe & Thelen, 2002*), thereby leading to reductions in the leaf area, aboveground dry matter, and photosynthetic products distributed to the maize ear, and ultimately to decreased grain yields (*Ciampitti & Vyn, 2011*; *Tokatlidis & Koutroubas, 2004*). Our results were similar but we also found that supplementary irrigation during the silking stage was helpful for increasing the yield at a high planting density. Using a combination of rainfall harvesting and supplementary irrigation in the semiarid areas of northwestern China, the optimal planting density for maize is 75,000 plants ha^{-1}, which is higher than the traditional planting density of 60000–68000 plants ha^{-1} described by *Dou, Yu & Yu (2013)*. This is mainly because the rainfall harvesting system provides a good hydrothermal environment for the growth of maize (*Liu et al., 2014*; *Wu et al., 2015*), thereby allowing further increases in the grain yield as the planting density increases. In our study, the medium planting density combined with the irrigation treatment during the silking stage achieved a higher average annual yield (13.2 t ha^{-1}), which was about 24.3% higher than that under the medium planting density treatment without irrigation.

Water shortage is the main factor that limits food production in arid and semiarid regions, and the traditional irrigation method that utilizes water in a wasteful manner cannot be maintained in this region due to the excessive consumption of water (*Deng et al., 2006*). The use of RFS to reduce the amount of irrigation is potentially interesting and it should be further explored. Simple and convenient irrigation schedules are useful for local farmers, especially water-saving irrigation techniques, which have great potential for crop production in the semiarid regions of China. Our results suggest that supplementary irrigation during the silking period under RFS may be an effective water-saving method for maize cultivation in semiarid areas.

CONCLUSION

Based on two years of field research, we showed that sowing 75,000 plants ha^{-1} and irrigation with 375 m^3 ha^{-1} in the silking stage is a reasonable water-saving cultivation technique for maize in a semiarid area. This method can increase the soil water storage capacity, photosynthetic capacity of the maize leaves, dry matter accumulation, and grain yields in semiarid areas with annual rainfall of approximately 400 mm. Compared with conventional planting, this method allows the planting density to be increased by 43% and halves the amount of irrigation water applied. Therefore, it can be used as a water-saving planting method for maize cultivation in order to cope with drought and water shortages in semiarid regions.

ADDITIONAL INFORMATION AND DECLARATIONS

Competing Interests

The authors declare there are no competing interests.

Author Contributions

- Donghua Liu, Qianmin Jia and Peng Zhang conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the paper, and approved the final draft.
- Juan Li conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, and approved the final draft.
- Xiaolong Ren and Zhikuan Jia conceived and designed the experiments, analyzed the data, authored or reviewed drafts of the paper, and approved the final draft.

Data Availability

The following information was supplied regarding data availability:

The raw measurements are available in the Supplemental File.

Supplemental Information

Supplemental information for this article can be found online at http://dx.doi.org/10.7717/peerj.9959#supplemental-information.

REFERENCES

Afzal A, Duiker SW, Watson JE. 2017. Leaf thickness to predict plant water status. *Biosystems Engineering* **156**:148–156 DOI 10.1016/j.biosystemseng.2017.01.011.

Ali S, Xu Y, Ahmad I, Jia Q, Ma X, Sohail A, Manzoor P, Arif M, Ren X, Cai T, Zhang J, Jia Z. 2019. The ridge-furrow system combined with supplemental irrigation strategies to improves radiation use efficiency and winter wheat productivity in semi-arid regions of China. *Agricultural Water Management* **213**:76–86 DOI 10.1016/j.agwat.2018.10.006.

Azizian A, Sepaskhah AR. 2014. Maize response to water, salinity and nitrogen levels: physiological growth parameters and gas exchange. *International Journal of Plant Production* **8(1)**:131–162.

Bolaños J, Edmeades GO. 1996. The importance of the anthesis-silking interval in breeding for drought tolerance in tropical maize. *Field Crops Research* **48(1)**:65–80 DOI 10.1016/0378-4290(96)00036-6.

Borrás L, Maddonni GA, Otegui ME. 2003. Leaf senescence in maize hybrids: plant population, row spacing and kernel set effects. *Field Crops Research* **82**:13–26 DOI 10.1016/S0378-4290(03)00002-9.

Carvalho RCD, Cunha A, Silva JMD. 2011. Photosynthesis by six portuguese maize cultivars during drought stress and recovery. *Acta Physiologiae Plantarum* **33(2)**:359–374 DOI 10.1007/s11738-010-0555-1.

Çakir R. 2004. Effect of water stress at different development stages on vegetative and reproductive growth of corn. *Field Crops Research* **89(1)**:1–16 DOI 10.1016/j.fcr.2004.01.005.

Chaves MM. 2002. How plants cope with water stress in the field? Photosynth and growth. *Annals of Botany* **89(7)**:907–916 DOI 10.1093/aob/mcf105.

Chen X, Hao MD. 2015. Low contribution of photosynthesis and water-use efficiency to improvement of grain yield in Chinese wheat. *Photosynthetica* **53(4)**:519–526 DOI 10.1007/s11099-015-0147-9.

Ciampitti IA, Vyn TJ. 2011. A comprehensive study of plant density consequences on nitrogen uptake dynamics of maize plants from vegetative to reproductive stages. *Field Crops Research* **121**:2–18 DOI 10.1016/j.fcr.2010.10.009.

Dai Z, Trettin CC, Li C, Amatya DM, Sun G, Li H. 2010. Sensitivity of Stream flow and Water Table Depth to Potential Climatic Variability in a Coastal Forested Watershed1. *Journal of the American Water Resources Association* **46(5)**:1036–1048.

Deng XP, Shan L, Zhang HP, Turner NC. 2006. Improving agricultural water use efficiency in arid and semiarid areas of China. *Agricultural Water Management* **80**:23–40 DOI 10.1016/j.agwat.2005.07.021.

Dou CY, Yu XQ, Yu JC. 2013. Effect of planting density under controlled irrigation on the growth and water consumption of *middle ground 77 maize*. *Agricultural Research in the Arid Areas* **31(2)**:141–145 (in Chinese).

Du T, Kang S, Sun J, Zhang X, Zhang P. 2010. An improved water use efficiency of cereals under temporal and spatial deficit irrigation in north China. *Agricultural Water Management* **97(1)**:66–74 DOI 10.1016/j.agwat.2009.08.011.

Eapen D, Barroso ML, Ponce G, Campo ME, Cassab GI. 2005. Hydrotropism: root growth responses to water. *Trends in Plant Science* **10**:44–50.

Echarte L, Andrade FH. 2003. Harvest index stability of argentinean maize hybrids released between 1965 and 1993. *Field Crops Research* **82**:1–12 DOI 10.1016/S0378-4290(02)00232-0.

Echarte L, Rothstein S, Tollenaar M. 2008. The response of leaf photosynthesis and dry matter accumulation to nitrogen supply in an older and a newer maize hybrid. *Crop Science* **48**:656–665 DOI 10.2135/cropsci2007.06.0366.

Eldoma IM, Li M, Zhang F, Li F. 2016. Alternate or equal ridge–furrow pattern: Which is better for maize production in the rain-fed semi-arid Loess Plateau of China? *Field Crops Research* **191**:131–138 DOI 10.1016/j.fcr.2016.02.024.

Ennahli S, Earl HJ. 2005. Physiological limitations to photosynthetic carbon assimilation in cotton under water stress. *Crop Science* **45**:2374–2382 DOI 10.2135/cropsci2005.0147.

Fabeiro C, Olalla F, De Juan JA. 2001. Yield and size of deficit irrigated potatoes. *Agricultural Water Management* **48(3)**:255–266 DOI 10.1016/S0378-3774(00)00129-3.

Fan TL, Yang Z, Wang JH, Wang SY. 2014. Effects of irrigation period and irrigation amount on seed production yield and water use of maize in Hexi, Gansu province. *Agricultural Research in the Arid Areas* **5**:1–6 (in Chinese).

Farnham DE. 2001. Row spacing, plant density, and hybrid effects on corn grain yield and moisture. *Agronomy Journal* **93**:1049–1053 DOI 10.2134/agronj2001.9351049x.

Farooq M, Mubshar H, Kadambot HMS. 2014. Drought stress in wheat during flowering and grain-filling periods. *Critical Reviews in Plant Sciences* **33**:331–349 DOI 10.1080/07352689.2014.875291.

Farquhar GD, Sharkey TD. 1982. Stomatal conductance and photosynthesis. *Annual Review of Plant Physiology and Plant Molecular Biology* **33**:317–345 DOI 10.1146/annurev.pp.33.060182.001533.

Feng GZ, Zhang YJ, Chen YL, Li Q, Chen FJ, Gao Q, Mi GH. 2016. Effects of nitrogen application on root length and grain yield of rain-fed maize under different soil types. *Agronomy Journal* **108**:1–10 DOI 10.2134/agronj15.0135.

Flexas J, Galmes J, Medrano H, Ribas-Carbo M. 2006. Keeping a positive carbon balance under adverse conditions: responses of photosynthesis and respiration to water stress. *Physiologia Plantarum* **127**:343–352 DOI 10.1111/j.1399-3054.2006.00621.x.

Gan Y, Siddique KHM, Turner NC, Li XG, Niu JY, Yang C. 2013. Chapter seven–ridge-furrow mulching systems—an innovative technique for boosting crop productivity in semiarid rain-fed environments. *Advances in Agronomy* **118**:429–476 DOI 10.1016/B978-0-12-405942-9.00007-4.

Hu Q, Pan F, Pan X, Zhang D, Yang N, Pan Z. 2014. Effects of a ridge-furrow micro-field rainwater-harvesting system on potato yield in a semi-arid region. *Field Crops Research* **166**:92–101 DOI 10.1016/j.fcr.2014.06.005.

Jia Q, Xu Y, Ali S, Sun L, Ding R, Ren X, Zhang P, Jia Z. 2018. Strategies of supplemental irrigation and modified planting densities to improve the root growth and lodging resistance of maize (Zea mays L.) under the ridge-furrow rainfall harvesting system. *Field Crops Research* **224**:48–59 DOI 10.1016/j.fcr.2018.04.011.

Jones HG. 2007. Monitoring plant and soil water status: established and novel methods revisited and their relevance to studies of drought tolerance. *Journal of Experimental Botany* **58(2)**:119–130.

Kang SZ. 2017. Food security, international agricultural trade, and economic growth in China. *The Journal of International Trade & Economic Development* **13(4)**:161–175.

Kang SZ, Zhang JH. 2004. Controlled alternate partial root zone irrigation: its physiological consequences and impact on water use efficiency. *European Journal of Agronomy* **55(407)**:2437–2446.

Kang SZ, Zhang L, Liang YL, Cai HJ, Warrick D. 2003. Effects of limited irrigation on yield and water use efficiency of winter wheat on the Loess Plateau of China. *Agricultural Systems* **78(3)**:355–367 DOI 10.1016/S0308-521X(03)00037-4.

Lavinsky AO, Magalhães PC, Diniz MM, Gomes-Jr CC, Castro EM, Ávila R. 2015. Root system traits and its relationship with photosynthesis and productivity in four maize genotypes under drought. *Cereal Research Communications* **44**:89–97.

Lawlor DW. 2002. Limitation to Photosynthesis in Water-stressed Leaves: Stomata vs. Metabolism and the Role of ATP. *Annals of Botany* **89(7)**:871–885 DOI 10.1093/aob/mcf110.

Liu XJ, Wang L, Zhang HL, Lu Y, Zhou LH. 2012. Study on maize quota supplementary irrigation system in yanghuang irrigation area of ningxia. *The International Journal of Water Resources and Environmental Engineering* **23(03)**:34–37 (in Chinese).

Li CJ, Wen XX, Wan XJ, Liu Y, Han J, Liao YC, Wu W. 2016. Towards the highly effective use of precipitation by ridge-furrow with plastic film mulching instead of relying on irrigation resources in a dry semi-humid area. *Field Crops Research* **188**:62–73.

Li M, Li WX. 2004. Effects of fertilizer and density on source–sink traits and yield of high-yielding maize in cold region. *Scientia Agricultura Sinica* **37(8)**:1130–1137 (in Chinese).

Lian YH, Ali S, Zhang XD, Wang TL, Liu Q, Jia QM, Jia ZK, Han QF. 2016. Nutrient and tillage strategies to increase grain yield and water use efficiency in semi-arid areas. *Agricultural Water Management* **178**:137–147 DOI 10.1016/j.agwat.2016.09.021.

Lin P, Qi H, Li C, Zhao M. 2016. Optimized tillage practices and row spacing to improve grain yield and matter transport efficiency in intensive spring maize. *Field Crops Research* **198**:258–268 DOI 10.1016/j.fcr.2016.08.012.

Liu J, Bu L, Zhu L, Luo S, Chen X, Li S. 2014. Optimizing plant density and plastic film mulch to increase maize productivity and water-use efficiency in semiarid areas. *Agronomy Journal* **106**:1138–1146.

Medrano H, Escalona JM, Bota J, Gulías J, Flexas J. 2002. Regulation of photosynthesis of c3 plants in response to progressive drought: stomatal conductance as a reference parameter. *Annals of Botany* **89(7)**:895–905 DOI 10.1093/aob/mcf079.

Morot-Gaudry JF. 1986. Relationship between photosynthesis and protein synthesis in maize: i. kinetics of translocation of the photoassimilated carbon from the ear leaf to the seed. *Plant Physiology* **80**:211–215 DOI 10.1104/pp.80.1.211.

Nikolaeva MK, Maevskaya SN, Voronin PY. 2017. Photosynthetic co2/h2o gas exchange and dynamics of carbohydrates content in maize leaves under drought. *Russian Journal of Plant Physiology* **64(4)**:536–542 DOI 10.1134/S1021443717030116.

Oury V, Tardieu F, Turc O. 2016. Ovary apical abortion under water deficit is caused by changes in sequential development of ovaries and in silk growth rate in maize. *Plant Physiology* **171(2)**:986–996.

Potters G, Pasternak TP, Guisez Y, Palme KJ, Jansen MAK. 2007. Stress-induced morphogenic responses: growing out of trouble? *Trends in Plant Science* **12(3)**:98–105.

Ren B, Liu W, Zhang J, Dong S, Liu P, Zhao B. 2017. Effects of plant density on the photosynthetic and chloroplast characteristics of maize under high-yielding conditions. *The Science of Nature* **104**:12 DOI 10.1007/s00114-017-1445-9.

Ren XL, Jia ZK, Chen XL. 2008. Rainfall concentration for increasing corn production under semiarid climate. *Agricultural Water Management* **95**:1293–1302 DOI 10.1016/j.agwat.2008.05.007.

Ren X, Sun D, Wang Q. 2016. Modeling the effects of plant density on maize productivity and water balance in the loess plateau of china. *Agricultural Water Management* **171**:40–48 DOI 10.1016/j.agwat.2016.03.014.

Rouhi V, Samson R, Lemeur R, Damme PV. 2007. Photosynthetic gas exchange characteristics in three different almond species during drought stress and subsequent recovery. *Environmental and Experimental Botany* **59(2)**:117–129 DOI 10.1016/j.envexpbot.2005.10.001.

Sarlangue T, Andrade FH, Calviño AP, Purcell CL. 2007. Why do maize hybrids respond differently to variations in plant density? *Agronomy Journal* **99**:984–991 DOI 10.2134/agronj2006.0205.

Souza RP, Machado EC, Silva JA, Lagoa AMM, Silveira JAG. 2004. Photosynthetic gas exchange, chlorophyll fluorescence and some associated metabolic change in cowpea Vigna unguiculata during water stress and recovery. *Environmental and Experimental Botany* **51**:45–56 DOI 10.1016/S0098-8472(03)00059-5.

Timlin DJ, Fleisher DH, Kemanian AR, Reddy VR. 2014. Plant Density and Leaf Area Index Effects on the Distribution of Light Transmittance to the Soil Surface in Maize. *Agronomy Journal* **106(5)**:1828–1837.

Tokatlidis IS, Koutroubas SD. 2004. A review of maize hybrids' dependence on high plant populations and its implications for crop yield stability. *Field Crops Research* **88**:103–114 DOI 10.1016/j.fcr.2003.11.013.

Vitale L, Tommasi PD, Arena C, Fierro A, Santo AVD, Magliulo V. 2007. Effects of water stress on gas exchange of field grown zea mays, l. in southern italy: an analysis at canopy and leaf level. *Acta Physiologiae Plantarum* **29(4)**:317–326 DOI 10.1007/s11738-007-0041-6.

Vitale L, Tommasi PD, Arena C, Riondino M, Forte A, Verlotta A. 2009. Growth and gas exchange response to water shortage of a maize crop on different soil types. *Acta Physiologiae Plantarum* **31(2)**:331–341 DOI 10.1007/s11738-008-0239-2.

Vu JCV, Baker JT, Pennanen HA, Allen Jr HL, Bowes G, Boote KJ. 1998. Elevated CO_2 and water deficit effects on photosynthesis, ribulose bisphosphate carboxylase-oxygenase, and carbohydrate metabolism in rice. *Journal of Plant Physiology* **103(3)**:327–339 DOI 10.1034/j.1399-3054.1998.1030305.x.

Wang Q, Ren X, Song XY, Hu GG, Zhang EH, Wang HL, Maureen MV. 2014. The optimum ridge–furrow ratio and suitable ridge-covering material in rainwater harvesting for oats production in semiarid regions of china. *Field Crops Research* **172**:106–118.

Wang Q, Song XY, Li FC, Hu GH, Zhang EH, Wang HL, Davies R. 2015. Optimum ridge-furrow ratio and suitable ridge-mulching material for Alfalfa production

in rainwater harvesting in semi-arid regions of China. *Field Crops Research* **180**:186–196 DOI 10.1016/j.fcr.2015.06.004.

Wang C, Wang ZQ, Zhang ZW, Lin TB. 2012. Effects of supplementary irrigation amount on photosynthesis and chlorophyll fluorescence characteristics of summer maize. *Agricultural Research in the Arid Areas* **30(06)**:99–106 (in Chinese).

Wang Y, Xie Z, Malhi SS, Vera CL, Zhang Y, Wang J. 2009. Effects of rainfall harvesting and mulching technologies on water use efficiency and crop yield in the semi-arid Loess Plateau, China. *Agricultural Water Management* **96(3)**:374–382 DOI 10.1016/j.agwat.2008.09.012.

Widdicombe WD, Thelen KD. 2002. Row width and plant density effect on corn forage hybrids. *Agronomy Journal* **94**:326–330 DOI 10.2134/agronj2002.0326.

Wu Y, Jia ZK, Ren XL, Zhang Y, Chen X, Bing HY, Zhang P. 2015. Effects of ridge and furrow rainwater harvesting system combined with irrigation on improving water use efficiency of maize (zea mays, L.) in semi-humid area of china. *Agricultural Water Management* **158**:1–9 DOI 10.1016/j.agwat.2015.03.021.

Xue Q, Zhu Z, Musick JT, Stewart BA, Dusek DA. 2003. Root growth and water uptake in winter wheat under deficit irrigation. *Plant Soil* **257(1)**:151–161 DOI 10.1023/A:1026230527597.

Zhang X, Wang ZH, Song ZZ, Zhang MY, Wang JZ. 2005. Study on the relationship between different densities of *zheng Dan 21* and yield and its components. *Maize Science* **13(1)**:106–107 (in Chinese).

Zhou LM, Li FM, Jin SL, Song Y. 2009. How two ridges and the furrow mulched with plastic film affect soil water, soil temperature and yield of maize on the semiarid loess plateau of china. *Field Crops Research* **113**:41–47 DOI 10.1016/j.fcr.2009.04.005.

Zhu GQ, Shi XG, Li QZ. 2001. Research on micro-water harvesting technology of spring wheat farmland in semi-arid areas of Ding Xi. *China Agrometeorology* **22(3)**:6–9 (in Chinese).