Using irrigation intervals to optimize water-use efficiency and maize yield in Xinjiang, northwest China

Guoqiang Zhang, Dongping Shen, Bo Ming, Ruizhi Xie, Xiuliang Jin, Chaowei Liu, Peng Hou, Jun Xue, Jianglu Chen, Wanxu Zhang, et al.

Available online at www.sciencedirect.com

ScienceDirect

Using irrigation intervals to optimize water-use efficiency and maize yield in Xinjiang, northwest China

Guoqiang Zhang[a,b,c,1], *Dongping Shen*[a,b,c,1], *Bo Ming*[b,c], *Ruizhi Xie*[b,c], *Xiuliang Jin*[d], *Chaowei Liu*[a], *Peng Hou*[b,c], *Jun Xue*[b,c], *Jianglu Chen*[e], *Wanxu Zhang*[a,b,c], *Wanmao Liu*[a,b,c], *Keru Wang*[b,c,*], *Shaokun Li*[a,b,c,*]

[a]*The Key Laboratory of Oasis Eco-agriculture, Xinjiang Production and Construction Group, College of Agronomy, Shihezi University, Shihezi 832000, Xinjiang, China*
[b]*Institute of Crop Sciences, Chinese Academy of Agricultural Sciences, Beijing 100081, China*
[c]*Key Laboratory of Crop Physiology and Ecology, Ministry of Agriculture, Beijing 100081, China*
[d]*UMR EMMAH, INRA, UAPV, 84914 Avignon, France*
[e]*Research Institute of Agricultural Sciences, Division 6 of Xinjiang Production and Construction Group, Wujiaqu 831300, Xinjiang, China*

A R T I C L E I N F O

Article history:
Received 23 July 2018
Received in revised form
11 October 2018
Accepted 25 December 2018
Available online 7 January 2019

Keywords:
Irrigation frequency
Soil moisture
Maize
High yield (>15 Mg ha^{-1})
Water use efficiency

A B S T R A C T

Worldwide, scarce water resources and substantial food demands require efficient water use and high yield. This study investigated whether irrigation frequency can be used to adjust soil moisture to increase grain yield and water use efficiency (WUE) of high-yield maize under conditions of mulching and drip irrigation. A field experiment was conducted using three irrigation intervals in 2016: 6, 9, and 12 days (labeled D6, D9, and D12) and five irrigation intervals in 2017: 3, 6, 9, 12, and 15 days (D3, D6, D9, D12, and D15). In Xinjiang, an optimal irrigation quota is 540 mm for high-yield maize. The D3, D6, D9, D12, and D15 irrigation intervals gave grain yields of 19.7, 19.1–21.0, 18.8–20.0, 18.2–19.2, and 17.2 Mg ha^{-1} and a WUE of 2.48, 2.53–2.80, 2.47–2.63, 2.34–2.45, and 2.08 kg m^{-3}, respectively. Treatment D6 led to the highest soil water storage, but evapotranspiration and soil-water evaporation were lower than other treatments. These results show that irrigation interval D6 can help maintain a favorable soil-moisture environment in the upper-60-cm soil layer, reduce soil-water evaporation and evapotranspiration, and produce the highest yield and WUE. In this arid region and in other regions with similar soil and climate conditions, a similar irrigation interval would thus be beneficial for adjusting soil moisture to increase maize yield and WUE under conditions of mulching and drip irrigation.

* *Corresponding authors at: Key Laboratory of Crop Physiology and Ecology, Ministry of Agriculture, Beijing 100081, China.*
E-mail addresses: wangkeru@caas.cn (K. Wang), lishaokun@caas.cn (S. Li).
Peer review under responsibility of Crop Science Society of China and Institute of Crop Science, CAAS.
[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.cj.2018.10.008

1. Introduction

China's food production is highly depend on irrigation [1], especially in north and northwest China, which have only 18% of China's water resources. Northern China accounts for as much as 65% of China's arable land [2] and 60% of the population, and groundwater in this region has been severely over-extracted [3]. In particular, in Xinjiang, which is a typical arid region of China, agricultural water accounts for over 90% of total water use. In arid and semiarid areas, water shortage is the main factor limiting crop yield. Deng et al. [4] reported an agricultural water-use efficiency (WUE) of 0.46 kg m^{-3} in the north and northwest of China. Irrigation water faces the double limitations of water shortage and low WUE. Thus, the development of water-efficient agriculture and the improvement of crop yield and WUE have high potential as effective measures to develop sustainable agriculture in irrigated areas.

Maize (*Zea mays* L.) is the most widely grown crop in China and plays an important role in ensuring China's food security [5]. Improving crop yield per unit land area is a key to solving the problem of food security. In modern maize production, increased yields per unit area come from increasing the optimum planting density [6,7]. Also, in arid regions, water is the major factor limiting agricultural yield. Drip irrigation and plastic film mulching are new agricultural water conservation technologies that have been widely used in crop production in recent years.

The time interval between irrigation applications is a crucial factor for drip-irrigation management because its affects soil-moisture distribution, root distribution, water uptake by roots, and water percolation under the root zone [8–12]. For these reasons, WUE and crop yield depend on irrigation interval and can thus differ even for the same total amount of irrigation. At each irrigation, excessive or inadequate water application can influence both WUE and grain yield. Although some studies [9,13] have shown that high irrigation frequency increases crop yield and WUE, others [14–16] have found that crop yield under low-frequency irrigation does not significantly differ from that obtained under high-frequency irrigation. This discrepancy may reflect the choice of different climatic conditions and different crops for study.

Irrigation frequency can change the spatial distribution of soil moisture and soil-water storage [17]. High-frequency drip irrigation (once every three days) produced higher soil moisture in the 0–20 cm soil layer than in the deep soil layer, whereas low-frequency drip irrigation (once every 10 days) favored water infiltration and lateral infiltration: deep soil moisture was higher, but the water supply was not timely and surface soil moisture was lower. Overall, medium-frequency drip irrigation (once every seven days) was beneficial to water infiltration and lateral infiltration. Medium-frequency drip irrigation is conducive to a uniform distribution of water in the soil profile [18]. Low irrigation frequency corresponds to excessively long irrigation intervals and may cause water stress, especially in sandy soils. It can also lead to substantial percolation below the root zone during irrigation because the irrigation amount at each irrigation may exceed the soil water-storage capacity. In contrast, an excessively high irrigation frequency might lead to desirable conditions for water uptake by roots, but at the price of increased energy and labor costs. If the irrigation amount is too small, soil water is distributed mainly on the surface and is insufficient to maintain crop growth, thereby causing water stress and increasing soil-water evaporation [19]. A suitable irrigation frequency can establish a balance between soil moisture and oxygen conditions in the crop root zone, reduce root soaking, and maintain a high soil matric potential in the rhizosphere to reduce plant water stress throughout the growing season [20]. Thus, optimizing irrigation frequency and water-application rate could help maximize crop yield and WUE [21]. The observation that several previous studies [22–25] have shown that high yield and WUE result from suitable irrigation frequency indicates that a frequent and uniform water supply is important for meeting the water requirements of plants and maximizing crop yield and WUE.

Drip-irrigation frequency affects soil-water distribution, and high-frequency irrigation increases potato tuber growth and WUE [12]. In salt-affected soil, a once-in-five-days frequency of drip irrigation under mulch leads to the most suitable soil-moisture range for cotton, whereas high-frequency (5 days) irrigation promotes soil-salt leaching in the root zone [26]. However, in sandy drip-irrigated soil, maize yield and WUE increase with increasing irrigation frequency and rate [27]. Subsurface drip-irrigation frequency does not affect maize production with deeper silt loam soils [14,28]. In normal years, irrigation frequency has no effect on grain yield under subsurface drip-irrigation; however, in dry years (with a seasonal precipitation of 415 mm or less) a high irrigation frequency can result in greater grain yield [21]. The differences in these results probably reflect differences in crops, irrigation technology, irrigation rate, climatic conditions, and/or soil texture. Thus, optimum irrigation frequency is not a constant, but is affected by soil conditions, climate conditions, irrigation conditions, and crop factors.

Our previous study [29] in Xinjiang investigated high-yield maize-irrigation technology and yielded an optimum irrigation quota of 540 mm for a high yield of 17.4 Mg ha^{-1} of maize with an irrigation interval of 9 days. To further explore and perfect ways to increase maize yield and WUE based on this irrigation quota, we hypothesized that increasing the irrigation frequency would further increase maize yield and WUE. The objectives of the present study were (1) to clarify how irrigation frequency affects soil moisture and (2) to determine whether irrigation frequency affects grain yield and WUE for maize. The results provide new insights into crop yield and WUE improvement in semi-arid and arid regions that should be helpful for improving irrigation technology and designing irrigation systems.

2. Materials and methods

2.1. Experimental region and site

A two-year field experiment was conducted from April to September in 2016 and 2017 at the Qitai Farm Experimental Station of the Chinese Academy of Agricultural Sciences (Xinjiang, China, 43°50′N, 89°46′E, altitude: 1020 m). The soil in the field is sandy loam whose main properties in the top

Table 1 – Soil physical and hydraulic parameters in the experimental field in 2016 and 2017.

Soil layer (cm)	Particle composition (%)			Bulk density ($g\ cm^{-3}$)	Field capacity ($g\ g^{-1}$)
	Clay	Silt	Sand		
0–20	22.6	37.1	40.3	1.27	23.55
20–40	24.3	33.8	41.9	1.29	23.03
40–60	22.4	34.0	43.6	1.30	22.86
60–80	18.7	36.1	45.2	1.32	22.60
80–100	20.4	36.8	42.8	1.32	22.57

layer (0–100 cm) are presented in Table 1. The average pH of the soil is 7.8 and the wilting point is 8.6% ($g\ g^{-1}$). The upper-60-cm soil profile contained 14.9 $g\ kg^{-1}$ of organic matter, 1.46 $g\ kg^{-1}$ total N, 99.7 $mg\ kg^{-1}$ available K, and 49.7 $mg\ kg^{-1}$ available P. These physical and chemical properties of the soil were measured at the beginning of each field experiment.

The climate in this region is characterized by minimal rainfall and many hours of sunshine. From 1997 to 2017, during the entire spring maize growing season (April–September), the mean precipitation was 158.6 mm, the mean daily temperature was 18.8 °C, the mean reference crop evapotranspiration was 1386.0 mm, and the mean total annual hours of sunshine was 1693.3 h. The precipitation was 208.2 mm (2016) and 166.0 mm (2017) during the growth period of maize. Fig. 1 shows climatic variables, including mean monthly precipitation distribution (Fig. 1-a), mean daily air temperature, and daily reference evapotranspiration (ET_o) (Fig. 1-b) during the seasons from 1997 to 2017. The daily reference evapotranspiration ET_o was determined using the FAO Penman–Monteith method [30]. Table 2 gives the precipitation, average air temperature, and sunshine hours during the 2016 and 2017 maize-growing period. Meteorological data were obtained from meteorological stations located at the farm experimental station.

2.2. Experiment design

The experiment included three irrigation-frequency treatments in 2016 and five in 2017. The local irrigation interval was used as the control interval (D9). The three irrigation intervals for 2016 were 6, 9, and 12 days (labeled D6, D9, and D12). The five irrigation intervals for 2017 were 3, 6, 9, 12, and 15 days (D3, D6, D9, D12, and D15). The total irrigation amount was the optimal amount (540 mm), as determined in a previous study [29] for drip irrigation with plastic-film mulching systems in arid regions. One day after sowing, 15 mm of water was applied to assure uniform, rapid germination. To prevent late lodging and to harden seedlings, no irrigation was applied from sowing to 60 days after sowing. Table 3 describes the irrigation strategies.

2.3. Irrigation system and agronomic practices

Zhengdan 958 (ZD958) and Xianyu 335 (XY335) are two commonly planted, high-yield, density-tolerant maize hybrids in China. ZD958 and XY335 were used in 2016, and XY335 was used in 2017. Maize was sown on April 18, 2016 and April 21, 2017 and harvested on October 18 in both 2016 and 2017. The planting density was 12 × 10^4 plants ha^{-1}. Plants were seeded in alternating wide and narrow rows at an alternating row spacing of 40–70–40 cm, and the spacing between plants within a row was 15 cm. Surface drip irrigation and plastic-film mulching were applied, and a combination planter [29] was used to apply drip tape and plastic film, punch holes, and manually sow. The area of each plot was 66 m^2 (10 m by 6.6 m). Each irrigation treatment included three replications. Water movement between plots was prevented by waterproof membranes buried at a depth of 1 m below the soil surface between each plot and by 1-m-wide buffer zones between plots.

Maize was drip-irrigated using water pumped from groundwater [29]. The drip irrigation system included single-

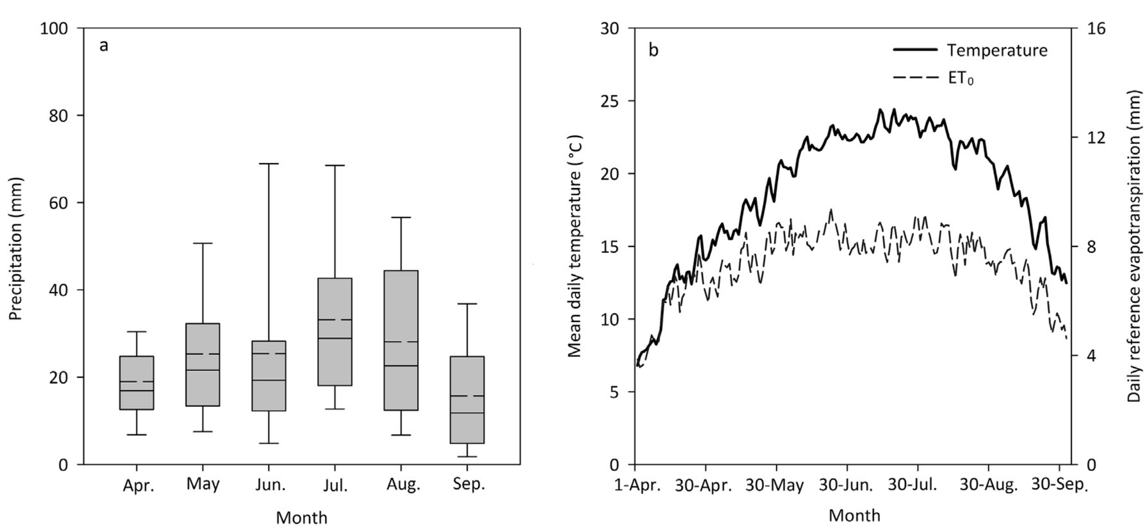

Fig. 1 – Changes in precipitation, temperature and reference evapotranspiration during spring maize growing seasons in Qitai for the period 1997–2017. (a) Mean monthly precipitation; (b) mean daily temperature and daily reference evapotranspiration.

Table 2 – Precipitation, average temperature, and sunshine hours during 2016 and 2017 maize-growth period.

Month	Precipitation (mm)		Average temperature (°C)		Sunshine hours (h)	
	2016	2017	2016	2017	2016	2017
April	17.7	20.4	14.8	13.0	6.9	6.2
May	31.7	42.7	15.0	16.9	7.9	9.2
June	75.6	72.2	22.6	21.1	8.4	7.3
July	42.1	0.9	23.3	24.1	7.8	9.8
August	36.5	18.9	21.8	20.9	7.1	8.9
September	4.6	10.9	19.6	15.7	8.9	8.3
Total or average	208.2	166.0	19.5	18.6	7.8	8.3

wing drip tape (Tianye Inc., Shihezi, China) placed in the middle of each narrow row. The emitter spacing was 30 cm and the flow rate was 3.2 L h^{-1} at an operating pressure of 0.1 MPa. Careful design and management led to stable discharge and pressure. Each plot was connected to a high-precision water meter (LXS-25F, Ningbo, China) and control valve.

Before sowing, base fertilizers were applied at concentrations of 150 kg ha^{-1} N (as urea), 225 kg ha^{-1} $(NH_4)_2HPO_4$ (ammonium phosphate), and 75 kg ha^{-1} K_2O (potassium sulfate). An additional 600 kg ha^{-1} urea was applied during the growing stage to ensure an adequate supply of nutrients. Chemical control (DA-6 Ethephon, China Agrotech, Shanxi, China) was applied at 600 mL ha^{-1} in the V8–V10 period of maize. All weeds, diseases, and pests in the experimental plots were controlled.

2.4. Sampling and measurements

2.4.1. Measurement of soil-moisture content

Soil-moisture content in 20-cm-thick soil layers (0–100 cm) was measured using the oven-drying method and a time-domain reflector (TDR, TRIME-T3, Germany). Five 100-cm-long tubes were deployed under the drip tape in all treatments after sowing and in each season. Samples were collected before sowing and physiological maturity, after rainfall, and one day before and after irrigation. Before sowing and physiological maturity, soil-moisture content was measured using the oven-drying method.

2.4.2. Evapotranspiration

Maize actual evapotranspiration ET_c (mm) was calculated during the growing season using the soil water balance equation [29]:

$$ET_c = I + P + C_r - R_f - D_p \pm \Delta S \tag{1}$$

where ET_c is evapotranspiration (mm) during the growing season, I is the amount of irrigation water applied (mm), P is precipitation (mm), C_r is capillary rise (mm), D_p is percolation (mm), R_f is runoff (mm), and ΔS is the change in soil-water storage (mm).

In Eq. (1), C_r is considered to be zero because the groundwater table was 70 to 80 m below the surface; runoff is also assumed to be insignificant because the field was flat, and D_p is considered negligible because the soil-water content below 100 cm did not reach field capacity (FC) on any sampling date.

2.4.3. Soil-water evaporation

Soil-water evaporation E_s was measured with a micro-lysimeter (MLS) [31–33]. The MLS consisted of two parts: an outer cylinder and an inner cylinder. The inner cylinder was made of steel pipe 10 cm in inner diameter and 15 cm long with a wall thickness of 1 mm. The outer cylinder was made of a PVC cylinder with inner diameter of 12 cm and length 15 cm. An electronic balance (ES6000, D&T, Tianjin, China) with a precision of 0.01 g was used for measuring mass. Three MLSs were placed in each plot and weighing was performed every day around sunset. The difference in weight over 2 days is the amount of evaporation, and a 1-g change in weight in the MLS corresponded to an evaporation of 0.127 mm. For each measurement, the inner cylinder was forced vertically into the soil and withdrawn to remove the soil. The bottom was sealed with aluminum foil and the soil was weighed, after which the inner cylinder was placed in the outer cylinder fixed between the widely spaced maize rows. To maintain the same soil moisture conditions in each plot, the original soil in the MLS was replaced every two days. The soil was replaced after precipitation or irrigation events.

The soil-water evaporation E_s per unit time can be calculated following [34,35]

$$E_s = \alpha\, \Delta m, \tag{2}$$

where E_s is soil-water evaporation (mm), α is a conversion factor (0.127 mm), and Δm (g) is the mass difference between MLS in one unit of time.

2.4.4. Water-use efficiency

Water-use efficiency was calculated as the ratio of grain yield to the total evapotranspiration for the whole season [36,37]:

$$WUE = GY/ET_c \tag{3}$$

Table 3 – Irrigation schedule for irrigation interval treatments in 2016 and 2017.

Treatments	Irrigation interval (day)	Single irrigation (mm)	Irrigation times
D3	3	25.00	21
D6	6	43.75	12
D9	9	58.33	9
D12	12	75.00	7
D15	15	87.50	6

where GY is grain yield (kg ha^{-1}) and ET_c is total evapotranspiration (mm) calculated from Eq. (1).

2.4.5. Grain yield

At physiological maturity, an area of 13.2 m^2 (central six rows of each plot, 4 m long) from three plots was harvested manually and the grain mass was measured. The plants and ears were counted and the number of ears per plant was determined. Kernel number per ear and 1000-kernel weight were measured for 20 representative ears per plot. Grain moisture content was determined with a portable moisture meter (PM8188, Kett Electric Laboratory, Japan). Grain yield was expressed at 14% moisture content and used for statistical analyses and calculation of WUE.

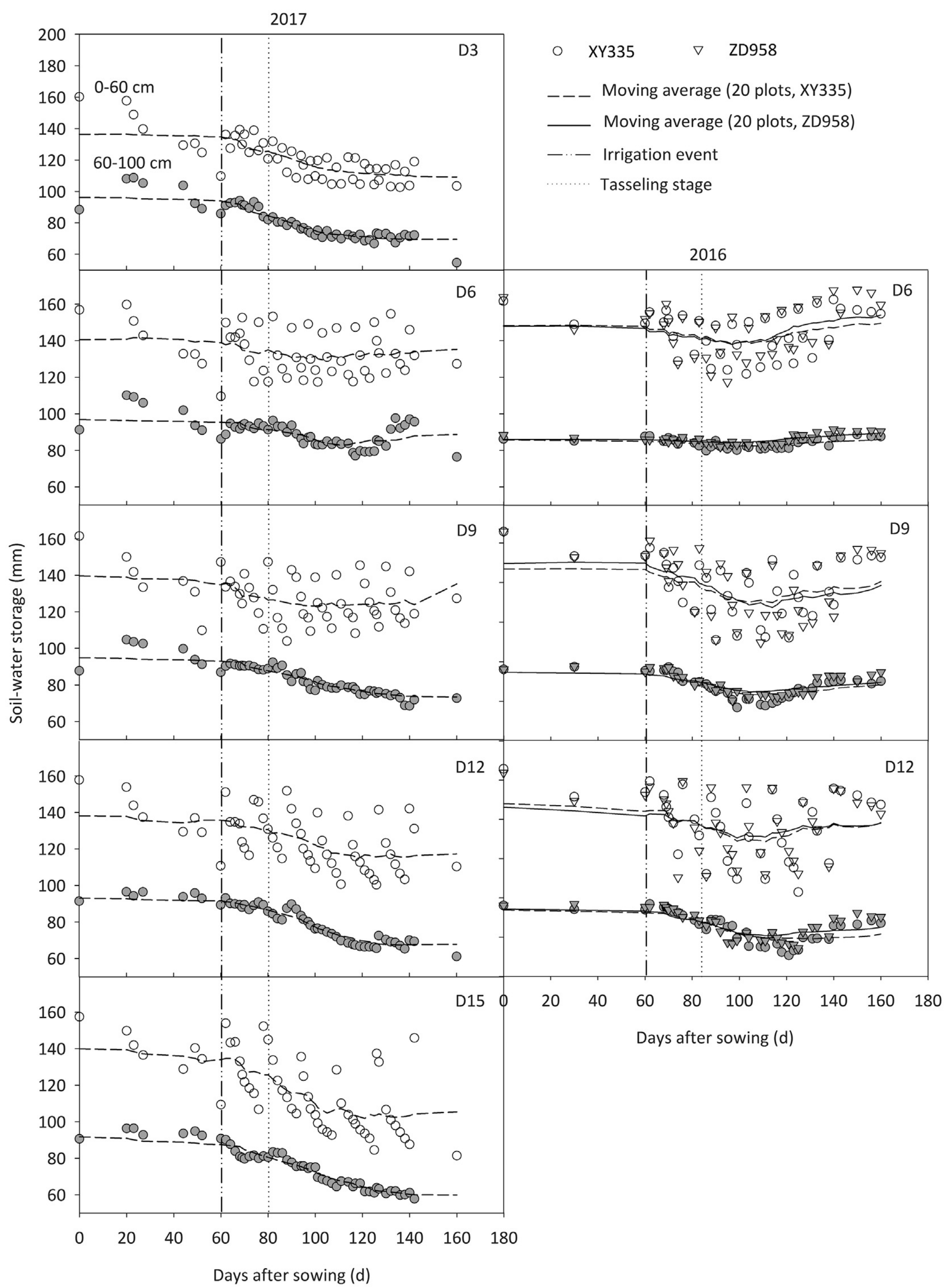

Fig. 2 – Soil-water storage as a function of days after sowing during the maize growing season in 2016 and 2017.

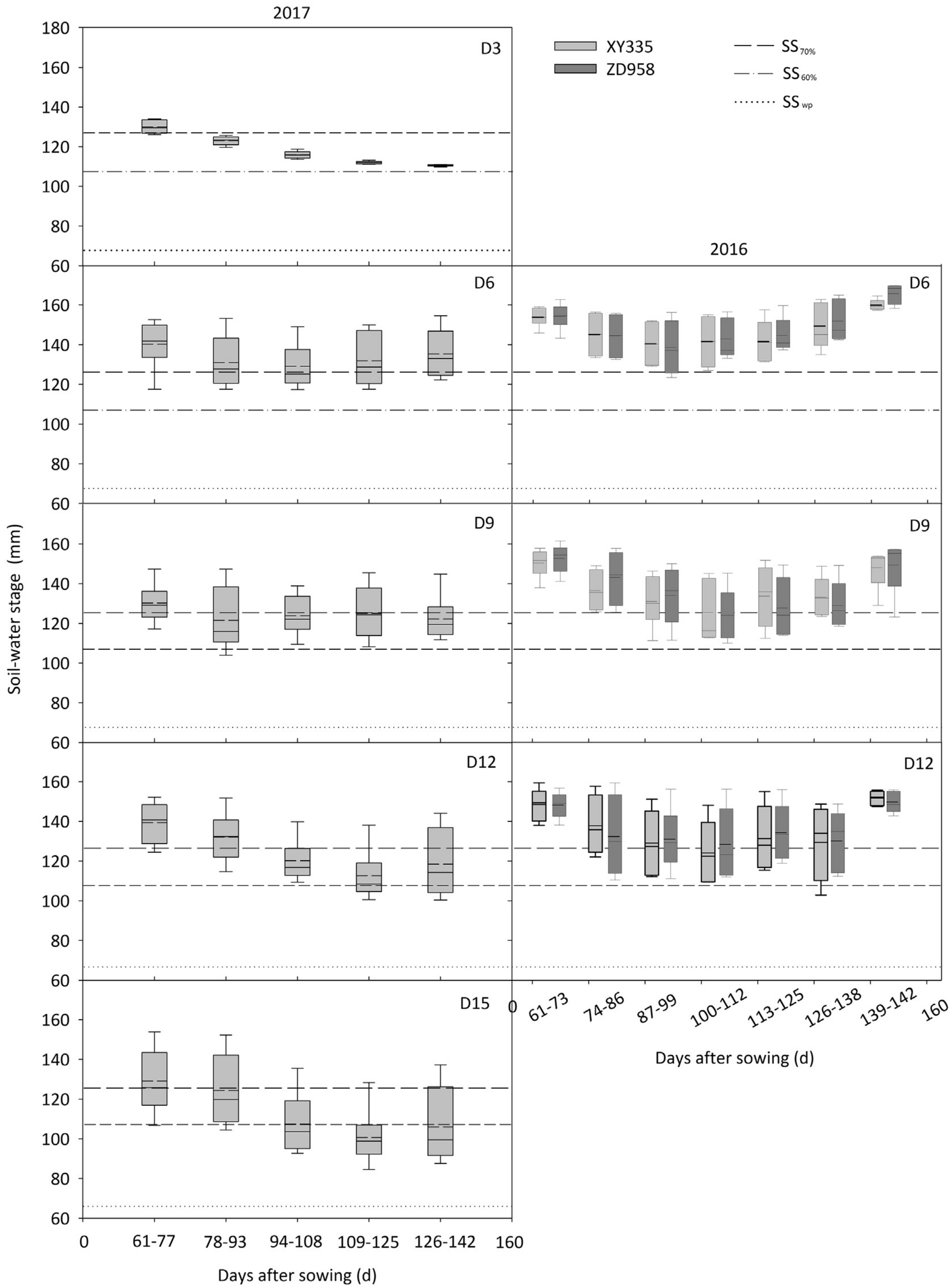

Fig. 3 – Effect of irrigation intervals on soil-water storage. The three broken lines represent the soil-water storage for different soil horizons corresponding to the 70% field capacity ($SS_{70\%}$, medium-dashed line), 60% ($SS_{60\%}$, short-dashed line), and wilting point (SS_{wp}, dotted line).

2.5. *Statistical analysis*

Calculations were performed and charts were prepared using Microsoft Excel 2013 (Microsoft Corporation, Redmond, Washington, USA) and SigmaPlot 12.5 (Systat Software Inc., San Jose, California, USA). Analysis of variance was used to test for differences in yield, WUE, and ET_c as a function of irrigation frequency. Correlation analysis was performed with SPSS 18.0 (SPSS Inc., Chicago, Illinois, USA) to determine the relationships between WUE and irrigation frequency and between WUE and ET_c. Means were compared using Fisher's least significant difference tests with $P < 0.05$ ($LSD_{0.05}$).

3. Results

3.1. Soil-water storage

Irrigation frequency significantly affected soil-water storage (SS) during the irrigation period (Fig. 2). Irrigation began at 61 days after sowing (DAS), and the SS of the 0–60 cm soil layer for each treatment varied great before and after irrigation. The range of variation increased with irrigation interval length. The SS in the 60–100 cm soil layer was relatively stable. Average SS values in the 0–60 cm soil layer for D3, D6, D9, D12, and D15 were 121.0, 134.2–148.9, 127.6–138.1, 125.4–137.7, and 117 mm, respectively. In the 60–100 cm soil layer, the average SS values for intervals were 80.3, 89.6–94.0, 83.7–89.0, 79.9–86.2, and 74.7 mm. SS was higher in 2016 than in 2017, and no great difference in SS occurred between XY335 and ZD958. In the 0–60-cm soil layer, the D6 irrigation treatment average SS varied from 134.2 to 148.9 mm throughout the irrigation period.

3.2. Effect of irrigation interval on soil water storage

During the irrigation period (61–142 DAS), SS varied in the 0–60 cm soil layer during the different growth stages (Fig. 3). Soil-water storage under treatment D6 exceeded that under the other treatments at all growth stages. Lower irrigation frequency corresponded to greater fluctuation in SS. We used $SS_{70\%}$ as the ideal lower limit and $SS_{60\%}$ as the lower limit for mild water stress, soil water storage status can also reflect how irrigation frequency affects soil-moisture status in different growth stages. Table 4 shows, for each irrigation treatment, the percent of days during the irrigation period that the SS attained the given levels.

The SS_{wp} was 66.3 mm. The number of days with SS exceeding $SS_{70\%}$ for treatment D6 was significantly greater than that under the other treatments. At $SS_{60\%}$, SS for treatments D12 and D15 declined significantly in the later period in 2017, indicating that these treatments led to some water deficit.

3.3. Soil-water evaporation

Irrigation frequency significantly affected soil-water evaporation E_s (Fig. 4). During 61–76 DAS, the average daily E_s of D6, D9, D12 were 1.12, 1.16, and 1.18 mm day^{-1} in 2016, and in 2017 the average daily E_s for treatments D3, D6, D9, D12, and D15 were 1.21, 1.1, 1.15, 1.23, and 1.29 mm day^{-1}. No significant difference in E_s between XY335 and ZD958 was observed in 2016.

Table 4 – Percent of days when soil water storage was at a different water storage horizon during irrigation period.

Treatment	Percent of days during irrigation period (%)		
	$>SS_{70\%}$	$SS_{60\%}$–$SS_{70\%}$	$<SS_{60\%}$
D3	26.7	55.6	17.8
D6	62.2–98.7	1.3–37.8	0.0
D9	44.4–73.7	30.3–53.3	0–2.2
D12	40.0–71.1	28.9–44.4	0–15.6
D15	28.9	22.2	48.9

The soil water storage in different soil horizons corresponding to the 70% ($SS_{70\%}$) and 60% ($SS_{60\%}$) field capacity.

3.4. Total soil-water storage

From 61 to 160 DAS, ET_c, SS (Fig. 5), and E_s (Fig. 6) differed significantly as a function of irrigation frequency. E_s for treatment D6 was great lower than for the other irrigation treatments, but SS was higher than for the other irrigation treatments. The results show that irrigation treatment D6 reduced E_s and thus ET_c. A suitable irrigation frequency can maintain SS at a relatively high level and maintain a favorable soil-moisture environment.

3.5. Grain yield, water-use efficiency, and evapotranspiration

Treatment D6 achieved high yield (19.1–21.0 Mg ha^{-1}) and WUE (2.53–2.80 kg m^{-3}) over both growing seasons (Table 5). The WUE for D6 was 8.3%, 4.8%, 11.7%, and 28.7% greater than that for D3, D9, D12, and D15, respectively. Maize yield and WUE are quadratically related to irrigation interval: $y_{grain\ yield} = -0.0316x^2 + 0.3391x + 19.153$, $R^2 = 0.701^{**}$; $y_{WUE} = -0.0082x^2 + 0.1096x + 2.2743$, $R^2 = 0.808^{**}$ (where x is irrigation interval). Evapotranspiration ET_c was significantly greater for treatment D15 than for the other treatments, and ET_c was significantly lower for treatment D6 than for the other treatments. Maize yield did not increase with ET_c, but WUE decreased as ET_c increased. Maize yield and WUE were exponentially related to ET_c: $y_{grain\ yield} = 80.83e^{-0.002x}$, $R^2 = 0.508^{*}$; $y_{WUE} = 28.107e^{-0.003x}$, $R^2 = 0.746^{**}$ (x is ET_c).

Comparing the same treatments, grain yield was 1.9% higher in 2017 than in 2016. In 2016, XY335 yield was significantly greater (5.2%) than ZD958 yield. This difference in yield may reflect the more numerous rainy days in 2016 and reduced sunshine time during the grain-filling stage. Differences in yield between cultivars reflect mainly the cultivar attributes.

4. Discussion

Irrigation frequency changed the spatial distribution of soil moisture and SS, when irrigation frequency increases, the upper-layer soil moisture increases within a certain range, and the upper soil layer storage increases. The appropriate irrigation frequency may thus increase the SS capacity. We reached conclusions similar to that of studies [12,17]. In the present study, the soil moisture was concentrated mainly in the 0–60 cm soil layer, and increasing the irrigation frequency reduced soil-moisture fluctuations in this upper soil layer. Treatment D6 maintained a high soil-moisture content throughout the irrigation period. Soil-water storage in late 2016 was higher than that in 2017, mainly because of higher SS before sowing in 2016, higher rainfall in July and August, more cloudy days and less sunshine. These factors inhibited soil-water evaporation and evapotranspiration and reduced the water consumption of maize, resulting in higher SS.

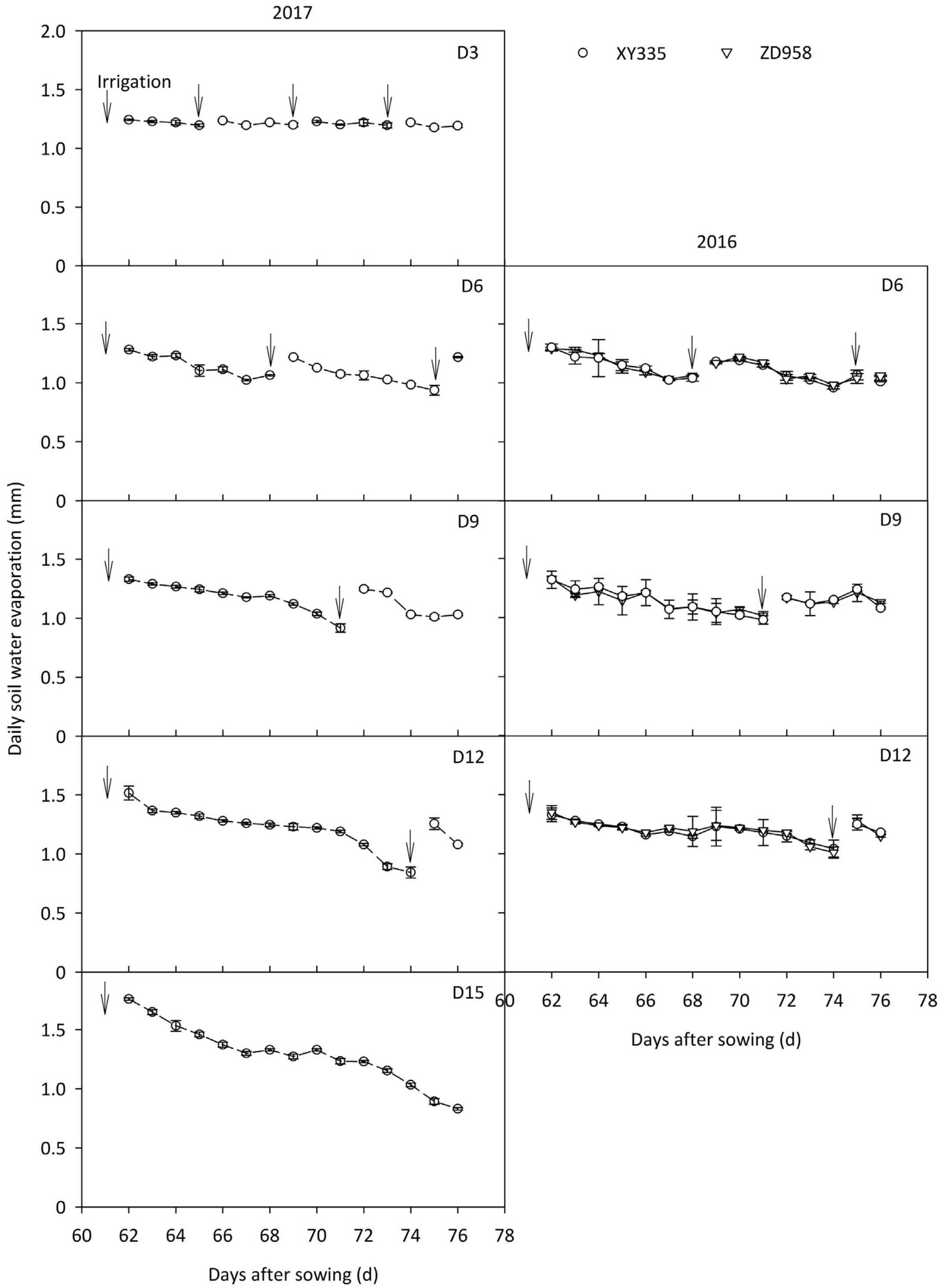

Fig. 4 – Soil-water evaporation under different irrigation intervals from 61 to 76 DAS in 2016 and 2017.

Different irrigation frequencies also lead to different SS. Studies [38] have shown that, for mulching plus drip irrigation in arid areas, the lower limit of irrigation is 65% FC, and obtained high yield. Previous studies [39–41] showed that 70% FC is the soil moisture content suitable for the key water-requirement period for maize. The classification of soil water stress and the determination of the lower limit of irrigation are affected by many factors, including soil environment, climate, mulching, irrigation amount, and irrigation frequency. Irrigation treatment D6 maintained a high soil-moisture regime, whereas the other treatments caused mild water stress. Thus, in future research, soil-water stress should be further analyzed and tested at different growth stages.

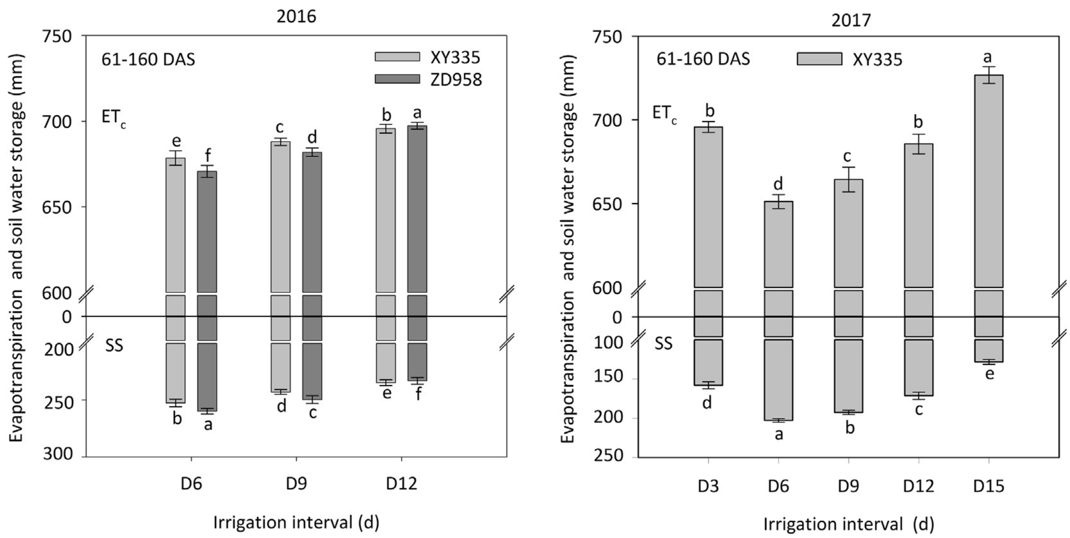

Fig. 5 – Evapotranspiration and soil water storage in the 0–100 cm soil layer at 61–160 days after sowing and for different irrigation intervals. ET$_c$, crop evapotranspiration; SS, soil water storage at 160 DAS. Means followed by different lowercase letters are significantly different at P < 0.05.

Treatment D6 led to the highest SS, but evapotranspiration and E_s were lower than other treatments. Thus, this irrigation treatment schedule balanced irrigation amount and the physiological and ecological water consumption of maize, thereby maintaining a favorable soil water environment. The negative correlation between soil-water storage and evapotranspiration indicates that a suitable irrigation frequency can increase the total amount of water in the soil [17,20].

Reducing E_s is important for improving WUE and saving water. The average E_s was lowest for treatment D6 from 61 to 76 DAS, and ranking the treatments in terms of E_s gives D15 > D12 > D3 > D9 > D6. Thus, E_s is one possible reason for the difference in soil moisture. The main factor is irrigation frequency: a single, high-volume irrigation leads to high E_s. Although film and mulching reduce E_s by 55%, uncovered soil (between widely spaced rows) still experiences copious evaporation. Soil-water evaporation and irrigation amount correlate positively and increase exponentially with surface soil moisture content [42,43]. A high irrigation frequency leads to more evaporation because of the high long-term water content at the soil surface, resulting in lower water storage in the soil layer [17]. Our findings followed these rules. An excessively high irrigation frequency causes a high E_s, as shown in the schematic diagram of Fig. 7. Thus, a suitable irrigation frequency reduces E_s and increases WUE. These results show that an irrigation frequency that is too high or

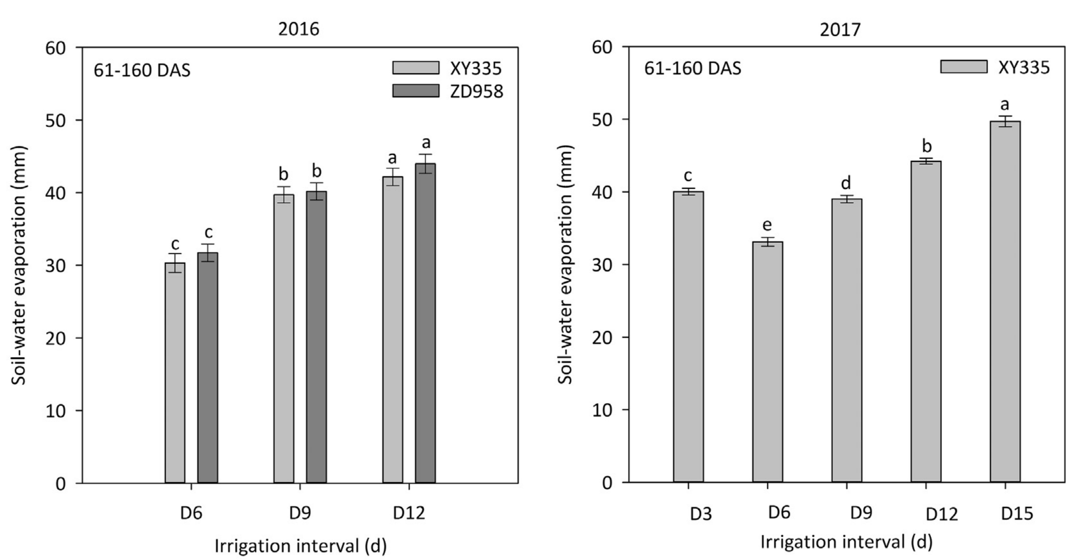

Fig. 6 – Soil-water evaporation at 61–160 days after sowing and for different irrigation intervals.

Table 5 – Grain yield, crop evapotranspiration, and water-use efficiency of maize for different irrigation treatments in 2016 and 2017.

Year	Cultivar	Irrigation interval	Grain yield (Mg ha^{-1})	WUE (kg m^{-3})	ET$_c$ (mm)
2016	ZD958	D6	19.1 a	2.53 a	750.2 c
		D9	18.8 b	2.47 b	760.4 b
		D12	18.2 c	2.34 c	776.9 a
		D6	20.6 a	2.71 a	757.4 c
	XY335	D9	19.8 b	2.58 b	767.1 b
		D12	18.7 c	2.41 c	775.3 a
2017	XY335	D3	19.7 b	2.48 c	795.6 b
		D6	21.0 a	2.80 a	750.1 e
		D9	20.0 b	2.63 b	761.5 d
		D12	19.2 c	2.45 c	782.1 c
		D15	17.2 d	2.08 d	825.0 a

Means within a column followed by different letters differ significantly at $P < 0.05$.

too low leads to ineffective soil-water evaporation. By reducing ineffective E_s, a suitable irrigation frequency thus helps maximize the use of soil moisture by crops.

Drip-irrigation plastic-film mulching is an effective way to save water, increase production, and improve WUE [44,45]. The grain yield of D6 was 20.7% greater than that (17.4 Mg ha^{-1}) of Zhang et al. [29] for the same area and conditions in Xinjiang. The previous study used nine-day irrigation intervals (D9). Thus, reducing the irrigation interval to six days increased the maize yield. Other work that supports this conclusion includes that of Irmak et al. [21], who showed that irrigation frequency affected grain yield significantly in dry years, and that high irrigation frequency led to higher grain yield (14.7 Mg ha^{-1}). Yazar et al. [22] reported that maize yields varied from 7.9 to 11.3 Mg ha^{-1} and 7.3 to 11.9 Mg ha^{-1} for three- and six-day irrigation intervals, respectively. Thus, a suitable irrigation frequency leads to high yield, in agreement with the results of previous studies [22,46]. However, a

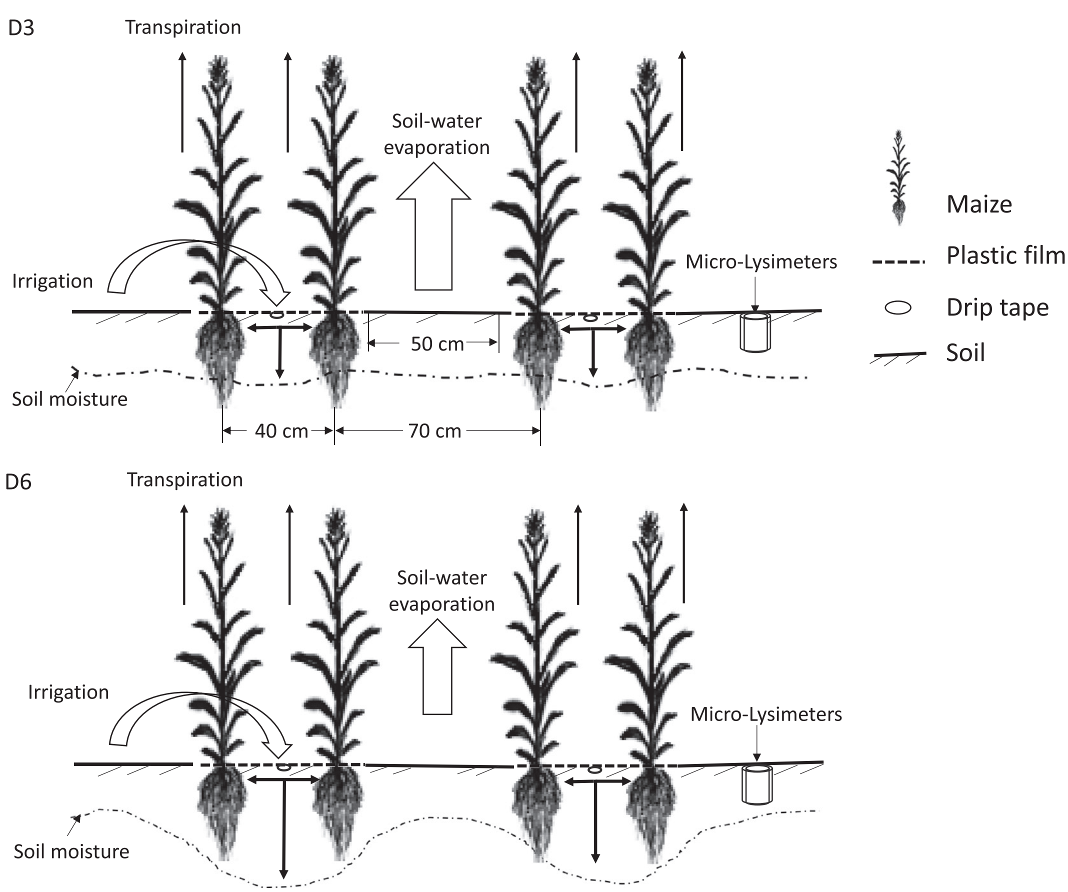

Fig. 7 – Schematic diagram of soil-moisture environment.

suitable irrigation frequency is affected by soil texture, weather condition, rainfall and irrigation rate. Thus, our findings may be applied in other arid regions with similar soil and climate conditions.

High WUE (a mean of 2.62 kg m^{-3}) was obtained in this study by application of a suitable irrigation amount (540 mm), which reduces evapotranspiration for mulching plus drip irrigation [29]. In this arid region, evapotranspiration is high, and irrigation intervals in local production are 9–15 days. However, the current irrigation interval is too long, lowering the yield of maize and the WUE. To further improve the yield and WUE of maize, we ran field trials for two years to identify the highest WUE (2.80 kg m^{-3}) for a suitable irrigation interval (6 days) and amount (540 mm). The WUE improved by 6.9% compared with previous work. In the present study, the WUE for treatment D6 was 6.5% and 12.9% greater than that for D9 and D3, respectively. We conclude that a suitable irrigation frequency leads to a high WUE, as in previous studies [9,22,25].

Low WUE is a common problem. Howell et al. [14] reported maize WUE from 1.08 to 1.62 kg m^{-3}, and Yazar et al. [22] reported that a six-day irrigation interval gave a high WUE (2.27 kg m^{-3}). Bozkurt et al. [47] obtained a WUE of 1.4 kg m^{-3}, and Kuscu et al. [48] reported a WUE from 1.40 to 1.93 kg m^{-3}. Hammad et al. [49] obtained a maize WUE of 1.04 to 1.55 kg m^{-3}, and Zhao et al. [50] obtained a WUE of 1.84 kg m^{-3}. However, compared with these studies, we obtained a higher WUE. The main reasons behind this result are the use of dense planting, plastic film mulching, drip irrigation, and an irrigation frequency increasing grain yield and reduce evapotranspiration. Thus, a suitable irrigation frequency leads to both high yield and high WUE.

Increased WUE can be achieved by coordinating maize yield and evapotranspiration. Maize yield can be optimized by use of high-yield hybrids, dense planting, mulching, drip irrigation, and water and fertilizer integration technologies. Reducing evapotranspiration can also increase WUE. Previous studies have shown that soil-water evaporation can be reduced by mulching [51–53], straw mulching [54], deficit irrigation [22,36,55], optimizing irrigation [29], and optimizing irrigation frequency [56,57] to increase WUE. We also conclude from the present study that a suitable irrigation frequency (D6 in this case) is conducive to reducing soil-water evaporation and improving WUE.

A shortcoming of the present study was that soil water stress was not recorded at different growth stages. Future studies should investigate how irrigation frequency affects dry matter production and photosynthesis in maize. Soil water stress and grading should also be recorded at different growth stages. Further study may show that tuning the irrigation frequency and irrigation amount at different growth stages can further increase grain yield and WUE.

5. Conclusions

Soil moisture, soil-water evaporation, evapotranspiration, yield, and WUE were investigated as a function of irrigation frequency and amount for drip irrigation with plastic-covered mulch. Given an irrigation quota of 540 mm, the optimum irrigation interval (6 days) helped the upper 60 cm soil layer maintain high water storage, producing a soil moisture environment favoring maize growth, reducing soil-water evaporation and ET_c, and thereby increasing maize yield and WUE. Grain yield reached 19.1 to 21.0 Mg ha^{-1} and WUE reached 2.53 to 2.80 kg m^{-3}. A suitable irrigation frequency thus helps optimize soil moisture and thereby increase maize yield and WUE. Adjustment of an irrigation frequency matched to the regional evapotranspiration is thus conducive to improving WUE. Similar management practices may be applied in other arid regions with similar soil and climate conditions.

Conflict of interest

The authors have declared that no conflict of interest.

Acknowledgments

We are grateful for research support from the National Key Research and Development Program of China (2016YFD0300110, 2016YFD0300101); the National Basic Research Program of China (2015CB150401); the National Natural Science Foundation of China (31360302); the Science and Technology Program of the Sixth Division of Xinjiang Construction Corps in China (1703); and the Agricultural Science and Technology Innovation Program for financial support of this study. We would also like to thank the reviewers for helping us improve our original manuscript.

REFERENCES

[1] J.X. Wang, Y.R. Li, J.K. Huang, T.T. Yan, T.H. Sun, Growing water scarcity, food security and government responses in China, Glob. Food Sec. 14 (2017) 9–17.

[2] S.L. Piao, P. Ciais, Y. Huang, Z.H. Shen, S.S. Peng, J.S. Li, L.P. Zhou, H.Y. Liu, Y.C. Ma, Y.H. Ding, P. Friedlingstein, C.Z. Liu, K. Tan, Y.K. Yu, T.Y. Zhang, J.Y. Fang, The impacts of climate change on water resources and agriculture in China, Nature 467 (2010) 43–51.

[3] S.Z. Kang, X.M. Hao, T.S. Du, L. Tong, X.L. Su, H.N. Lu, X.L. Li, Z.L. Huo, S.E. Li, R.S. Ding, Improving agricultural water productivity to ensure food security in China under changing environment: from research to practice, Agric. Water Manag. 179 (2017) 5–17.

[4] X.P. Deng, L. Shan, H. Zhang, N.C. Turner, Improving agricultural water use efficiency in arid and semi-arid areas of China, Agric. Water Manag. 80 (2006) 23–40.

[5] S.K. Li, J.R. Zhao, S.T. Dong, M. Zhao, C.H. Li, Y.H. Cui, Y.H. Liu, J.L. Gao, J.Q. Xue, L.C. Wang, P. Wang, W.P. Lu, J.H. Wang, Q.F. Yang, Z.M. Wang, Advances and prospects of maize cultivation in China, Sci. Agric. Sin. 50 (2017) 1941–1959 (in Chinese with English abstract).

[6] M. Tollenaar, E.A. Lee, Yield potential, yield stability and stress tolerance in maize, Field Crop Res. 75 (2002) 161–169.

[7] P. Grassini, J. Thorburn, C. Burr, K.G. Cassman, High-yield irrigated maize in the Western U.S. Corn Belt: I. On-farm yield, yield potential, and impact of agronomic practices, Field Crop Res. 120 (2011) 142–150.

[8] S. Assouline, The effects of micro drip and conventional drip irrigation on water distribution and uptake, Soil Sci. Soc. Am. J. 66 (2002) 1630–1636.

[9] S.E. El-Hendawy, E.M. Hokam, U. Schmidhalter, Drip irrigation frequency: the effects and their interaction with nitrogen fertilization on sandy soil water distribution, maize yield and water use efficiency under Egyptian conditions, J. Agron. Crop Sci. 194 (2008) 180–192.

[10] M.X. Liu, J.S. Yang, X.M. Li, M. Yu, J. Wang, Numerical simulation of soil water dynamics in a drip irrigated cotton field under plastic mulch, Pedosphere 23 (2013) 620–635.

[11] B. Zhou, Y.K. Li, Y.Z. Liu, F.P. Xu, Y.T. Pei, Z.H. Wang, Effect of drip irrigation frequency on emitter clogging using reclaimed water, Irrig. Sci. 33 (2015) 221–234.

[12] F.X. Wang, Y.H. Kang, S.P. Liu, Effects of drip irrigation frequency on soil wetting pattern and potato growth in North China Plain, Agric. Water Manag. 79 (2006) 248–264.

[13] M.X. Liu, J.S. Yang, X.M. Li, G.M. Liu, M. Yu, J. Wang, Distribution and dynamics of soil water and salt under different drip irrigation regimes in northwest China, Crop Sci. 31 (2013) 675–688.

[14] T.A. Howell, A.D. Schneider, S.R. Evett, Subsurface and surface micro-irrigation of corn-southern high plains, Trans. ASAE 40 (1997) 635–641.

[15] B.R. Hanson, D.M. May, L.J. Schwankl, Effect of irrigation frequency of subsurface drip irrigated vegetables, Hort. Technol. 13 (2003) 115–120.

[16] K. Uçan, F. Kıllı, C. Gençoğlan, H. Merdun, Effect of irrigation frequency and amount on water use efficiency and yield of sesame (*Sesamum indicum* L.) under field conditions, Field Crop Res. 101 (2007) 249–258.

[17] H.X. Cao, S.Z. Kang, H. He, Effects of evaporation and irrigation frequency on soil water distribution, Trans. CSAE 19 (2003) 1–4 (in Chinese with English abstract).

[18] M.X. Liu, J.S. Yang, X.M. Li, M. Yu, J. Wang, Effects of irrigation amount and frequency on soil water distribution and water use efficiency in a cotton field under mulched drip irrigation, Chin. J. Appl. Ecol. 22 (2011) 3203–3210 (in Chinese with English abstract).

[19] J.E. Jordan, R.H. White, D.M. Vietor, T.C. Hale, J.C. Thomas, M. C. Engelke, Effect of irrigation frequency on turf quality, shoot density, and root length density of five bent grass cultivars, Crop Sci. 43 (2003) 282–287.

[20] S.Q. Wan, Y.H. Kang, Effect of drip irrigation frequency on radish (*Raphanus sativus* L.) growth and water use, Irrig. Sci. 24 (2006) 161–174.

[21] S. Irmak, K. Djaman, D.R. Rudnick, Effect of full and limited irrigation amount and frequency on subsurface drip-irrigated maize evapotranspiration, yield, water use efficiency and yield response factors, Irrig. Sci. 34 (2016) 271–286.

[22] A. Yazar, S.M. Sezen, B. Gencel, Drip irrigation of corn in the Southeast Anatolia Project (GAP) Area in Turkey, Irrig. Drain. 51 (2002) 293–300.

[23] A. Ertek, S. Şensoy, C. Küçükyumuk, İ. Gedik, Irrigation frequency and amount affect yield components of summer squash (*Cucurbita pepo* L.), Agric. Water Manag. 67 (2004) 63–76.

[24] S. Sensoy, A. Ertek, I. Gedik, C. Kucukyumuk, Irrigation frequency and amount affect yield and quality of field-grown melon (*Cucumis melo* L.), Agric. Water Manag. 88 (2007) 269–274.

[25] D. Yavuz, N. Yavuz, M. Seymen, Ö. Türkmen, Evapotranspiration, crop coefficient and seed yield of drip irrigated pumpkin under semi-arid conditions, Sci. Hortic. 197 (2015) 33–40.

[26] P.F. Yi, T. Hudan, Y.M. Wang, Z.G. Wu, J.Z. Zhang, Schedule optimization of under-plastic-mulch drip irrigation for cotton in arid areas, Bull. Soil Water Conserv. 1 (2011) 53–57 (in Chinese with English abstract).

[27] S.E. El-Hendawy, U. Schmidhalter, Optimal coupling combinations between irrigation frequency and rate for drip-irrigated maize grown on sandy soil, Agric. Water Manag. 97 (2010) 439–448.

[28] D.S. Caldwell, W.E. Spurgeon, H.L. Manges, Frequency of irrigation for subsurface drip-irrigated corn, Trans. ASAE 37 (1994) 1099–1103.

[29] G.Q. Zhang, C.W. Liu, C.H. Xiao, R.Z. Xie, B. Ming, P. Hou, G.Z. Liu, W.J. Xu, D.P. Shen, K.R. Wang, S.K. Li, Optimizing water use efficiency and economic return of super high yield spring maize under drip irrigation and plastic mulching in arid areas of China, Field Crop Res. 211 (2017) 137–146.

[30] R.G. Allen, L.S. Pereira, D. Raes, M. Smith, Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements, FAO Irrigation and Drainage Paper NO. 56, FAO, Rome, Italy, 1998.

[31] C.W. Boast, T.M. Robertso, A “micro-lysimeter” method for determining evaporation from bare soil description and laboratory evaluation, Soil Sci. Soc. Am. J. 46 (1982) 689–696.

[32] C. Zhang, H.F. Yan, H.B. Shi, H. Sugimoto, Study of crop coefficient and the ratio of soil evaporation to evapotranspiration in an irrigated maize field in an arid area of Yellow River Basin in China, Meteorog. Atmos. Phys. 121 (2013) 207–214.

[33] Z. Wei, P. Paredes, Y. Liu, W.W. Chi, L.S. Pereira, Modelling transpiration, soil evaporation and yield prediction of soybean in North China Plain, Agric. Water Manag. 147 (2015) 43–53.

[34] W.Q. Liang, H.F. Cai, J. Wang, Research evapotranspiration and evaporation for winter wheat, J. Irrig. Drain. 6 (2011) 93–96 (in Chinese with English abstract).

[35] L. Wang, T. Lin, C.R. Yan, J. Wang, R.X. Guo, L.K. Yue, Q.X. Tang, Effects of plastic film residue on evapotranspiration and soil evaporation in cotton field of Xinjiang, Trans. CSAE 32 (2016) 120–128 (in Chinese with English abstract).

[36] S.Z. Kang, W.J. Shi, J.H. Zhang, An improved water-use efficiency for maize grown under regulated deficit irrigation, Field Crop Res. 67 (2000) 207–214.

[37] J.O. Payero, D.D. Tarkalson, S. Irmak, D. Davison, J.L. Petersen, Effect of irrigation amounts applied with subsurface drip irrigation on corn evapotranspiration, yield, water use efficiency, and dry matter production in a semiarid climate, Agric. Water Manag. 95 (2008) 895–908.

[38] Z.L. Wang, P.G. Dong, X.K. Fan, T.R. Wang, Effects of irrigation quota on distribution of soil water-salt and yield of spring maize with drip irrigation under mulch, Sci. Agric. Sin. 49 (2016) 2343–2352 (in Chinese with English abstract).

[39] J.F. Xiao, Z.D. Liu, J.Q. Nan, X.Q. Yu, Effects of different moisture treatments on ecological index, water consumption and yield of spring maize, J. Maize Sci. 18 (2010) 94–97 101. (in Chinese with English abstract).

[40] W.H. Li, G.H. Yin, J. Gu, P.F. Huang, Z.B. Jia, Coupling effects of water and nitrogen on yield and water use efficiency of spring maize with drip irrigation under film mulching, Chin. J. Ecol. 34 (2015) 3397–3401 (in Chinese with English abstract).

[41] S.S. Wang, D.X. Liu, K.S. Wang, P.T. Meng, Fuzzy comprehensive evaluation on water consumption characteristics and yield of summer corn under different furrow irrigation patterns, Trans. CSAE 31 (2015) 89–94 (in Chinese with English abstract).

[42] J.S. Sun, S.Z. Kang, J.L. Wang, X.D. Li, N. Song, Experiment on soil evaporation of summer maize under furrow irrigation condition, Trans. CSAE 21 (2005) 20–24 (in Chinese with English abstract).

[43] C. Zhao, Q. Chai, F.X. Feng, W. Yin, F.L. Hu, W.B. Zhou, Characteristics and economic benefits of water consumption in intercropping fields with one plastic film mulching for 2 years and different irrigation levels, Chin. J. Eco-Agric. 24 (2016) 744–752 (in Chinese with English abstract).

[44] T.S. Du, S.Z. Kang, J.H. Zhang, F.S. Li, Water use and yield responses of cotton to alternate partial root-zone drip irrigation in the arid area of north-west China, Irrig. Sci. 26 (2008) 147–159.
[45] S.J. Qin, S.E. Li, S.Z. Kang, T.S. Du, L. Tong, R.S. Ding, Can the drip irrigation under film mulch reduce crop evapotranspiration and save water under the sufficient irrigation condition? Agric. Water Manag. 177 (2016) 128–137.
[46] A. Oktem, M. Simsek, A.G. Oktem, Deficit irrigation effects on sweet corn (*Zea mays saccharata* Sturt) with drip irrigation system in a semi-arid region, Agric. Water Manag. 61 (2003) 63–74.
[47] Y. Bozkurt, A. Yazar, B. Gencel, M.S. Sezen, Optimum lateral spacing for drip-irrigated corn in the Mediterranean region of Turkey, Agric. Water Manag. 85 (2006) 113–120.
[48] H. Kuscu, A. Karasu, M. Oz, A.O. Demir, I. Turgut, Effect of irrigation amounts applied with drip irrigation on maize evapotranspiration, yield, water use efficiency, and net return in a sub-humid climate, Turk. J. Field Crops 18 (2013) 13–19.
[49] H.M. Hammad, A. Ahmad, F. Abbas, W. Farhad, B.C. Cordoba, G. Hoogenboom, Water and nitrogen productivity of maize under semiarid environments, Crop Sci. 55 (2015) 877–888.
[50] J. Zhao, Q.W. Xue, K.E. Jessup, B.Z. Hao, X.B. Hou, T.H. Marek, W. Xu, S.R. Evett, S.A. O'Shaughnessy, D.K. Brauer, Yield and water use of drought-tolerant maize hybrids in a semiarid environment, Field Crop Res. 216 (2018) 1–9.
[51] L.D. Bu, J.L. Liu, L. Zhu, S.S. Luo, X.P. Chen, S.Q. Li, R.L. Hill, Y. Zhao, The effects of mulching on maize growth, yield and water use in a semi-arid region, Agric. Water Manag. 123 (2013) 71–78.
[52] S.L. Zhang, V. Sadras, X.P. Chen, F.S. Zhang, Water use efficiency of dryland maize in the Loess Plateau of China in response to crop management, Field Crop Res. 163 (2014) 55–63.
[53] Q. Li, H.B. Li, L. Zhang, S.Q. Zhang, Y.L. Chen, Mulching improves yield and water-use efficiency of potato cropping in China: a meta-analysis, Field Crop Res. 221 (2018) 50–60.
[54] Z.X. Yan, C. Gao, Y.J. Ren, R. Zong, Y.Z. Ma, Q.Q. Li, Effects of pre-sowing irrigation and straw mulching on the grain yield and water use efficiency of summer maize in the North China Plain, Agric. Water Manag. 186 (2017) 21–28.
[55] E. Fereres, M.A. Soriano, Deficit irrigation for reducing agricultural water use, J. Exp. Bot. 58 (2007) 147–159.
[56] A. Oktem, Effect of different irrigation intervals to drip irrigated dent corn (*Zea mays* L. *indentata*) water-yield relationship, Pak. J. Biol. Sci. 9 (2006) 1476–1481.
[57] A.A. Abd El-Halim, U.A. Abd El-Razek, Effect of different irrigation intervals on water saving, water productivity and grain yield of maize (*Zea mays* L.) under the double ridge-furrow planting technique, Arch. Agron. Soil Sci. 60 (2014) 587–596.