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Improving Water Use Efficiency of Spring Maize by Adopting Limited Supplemental Irrigation Following Sufficient Pre-Sowing Irrigation in Northwest China

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Received: 11 March 2019; Accepted: 12 April 2019; Published: 17 April 2019

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Abstract: In order to improve the water use efficiency (WUE) of spring maize in northwest China, the irrigation strategy of adopting limited supplemental irrigation following a high quota pre-sowing irrigation was evaluated under field conditions in 2016 and 2018. There were three treatments (W1, W2 and W3) differing in designed wetting depth (D_h) where soil water was replenished. D_h in W1, W2 and W3 were 0–40, 0–50 and 0–60 cm, respectively. The limited supplemental irrigation was adopted to improve soil water content (SWC) within D_h to field capacity (θ_{FC}) when SWC within 0–40 cm layer decreased to 60%θ_{FC} following a high rate of pre-sowing irrigation. Results showed that the smaller D_h was beneficial for improving root length density and enhance the utilization of water in subsoil. In both seasons, different D_h led to similar grain yields, which were comparable to the typical regional yield (14.3 t ha^{-1}). The highest WUE (2.79 kg m^{-3}) was achieved in W1 and was 13% more than the typical regional level of 2.46 kg m^{-3}, implying it was adequate for achieving high yield and WUE to maintain SWC in 0–40 cm above 60% θ_{FC} with not replenishing soil water in 40–100 cm during the growth season after pre-sowing irrigation.

Keywords: spring maize; irrigation strategy; designed wetting depth; grain yield; water use efficiency

1. Introduction

There is a serious shortage of water resources in arid areas of northwest China, where annual potential evaporation is more than 1500 mm with less than 200 mm precipitation [1]. Irrigation is necessary to achieve high yield. As the main source of irrigation water, groundwater has a rapid decrease in recent years and it is difficult to guarantee irrigation in the region [2,3]. This is exacerbated by the inappropriate irrigation strategy applied in local area. Pre-sowing irrigation is adopted generally before sowing due to less precipitation during the sowing period of spring maize in northwest China [4,5]. The 105 mm pre-sowing irrigation is recommended by Wang et al. [5], who optimized the quota of pre-sowing irrigation in spring maize production in the study region. The pre-sowing irrigation is sufficient to replenish soil water content (SWC) in soil profile of 0–1 m to field capacity. Following that, a high irrigation quota (90 mm or even more) is applied in each irrigation event because it is convenient for soil water management in field [4–8]. Soil water in subsoil is replenished again and maintains at high level in the whole growth period. As a large portion of irrigated water in lower part of root zone cannot be easily used by plant roots, this strategy of irrigation is likely to cause deep water percolation and represent a large portion of water resources waste [9]. Furthermore, the high quota of irrigation during growth season has a high risk of leaching of soil nitrogen [10]. To enable sustainable crop production, optimization of irrigation strategy during growth season for achieving high yield with enhanced water use efficiency (WUE) is needed for arid areas in northwest China.

Roots distribute mainly near the subsurface and the top 45 cm soil layer contains more than 80% of the total root lengths which supply more than 65% of the total water consumption of maize [11,12]. The effectiveness of soil water in root zone on water status of plants is significantly influenced by the distribution pattern of roots [13,14]. Soil water condition of the upper soil layer plays a determinant role in transpiration and crop yield [11,15]. Additionally, soil water content in lower part of root zone maintains at high level for a long time after sufficient pre-sowing irrigation. This implies that the replenishment of soil water can be restricted to the upper soil layers without severe loss of crop yield. Geneille et al. [15] have found that the designed wetting depth (D_h) of 0–60 cm where soil water is replenished is adequate for achieving a high yield in surface irrigated maize production. Furthermore, under the limited supplemental irrigation which replenishing soil water in part of root zone, the SWC in root zone showed a decreasing trend with time [15]. It is possible to design a supplemental irrigation strategy with smaller D_h to impose a mild water deficit. The previous researches have reported that mild water deficit does not lead to serious losses in yield, even increases production and is beneficial to improve WUE [16,17]. We hypothesized that WUE can be improved with high yield by adopting limited supplemental irrigation following a high quota pre-sowing irrigation. However, the suitable D_h to achieve the optimal supplemental irrigation strategy is unknown.

In this study, sufficient pre-sowing irrigation which replenishes soil water in soil profile of 0–1 m to field capacity was applied uniformly for all the treatments. The objective was to examine the differences in soil available water dynamics, crop growth, physiology traits, WUE and grain yield of spring maize among supplemental irrigation strategies during growth season with different D_h and then to determine the optimal D_h.

2. Methods

2.1. Study Area

Field experiments were conducted in 2016 and 2018 at the Shiyang River Basin Experiment Station (37°52′ N, 102°50′ E, altitude 1581 m) in Wuwei City, China. The climate in the experimental site is characterized as a temperate continental arid, with average annual precipitation of 164 mm and pan evaporation of 2000 mm. The exchange of soil water in root zone (0–1 m) with groundwater can be ignored due to the groundwater table over 40 m below ground surface at this site [8]. Soil samples collected at 20 cm intervals down to a 1 m soil depth using the 5-point diagonal sampling method [18] in April 2016 were used to determine the basic soil properties in experimental filed (Table 1). Daily precipitation and average air temperature during the growing season in 2016 and 2018 are presented in Figure 1.

Table 1. Soil properties of the experimental field at the Shiyang River Basin Experiment Station.

Soil Layer (cm)	Texture (%)			Bulk Density ($g\ cm^{-3}$)	Saturated Hydraulic Conductivity ($cm\ h^{-1}$)	Field Capacity ($cm^3\ cm^{-3}$)	Wilting Point ($cm^3\ cm^{-3}$)
	Sand	Silt	Clay				
0~20	71.5	14.7	13.8	1.54	1.21	0.23	0.10
20~40	71.1	13.2	15.7	1.58	0.52	0.25	0.12
40~60	40.9	41.1	18.0	1.48	0.76	0.28	0.14
60~80	24.0	63.3	13.7	1.32	1.23	0.32	0.15
80~100	21.3	68.1	10.6	1.42	0.98	0.32	0.15

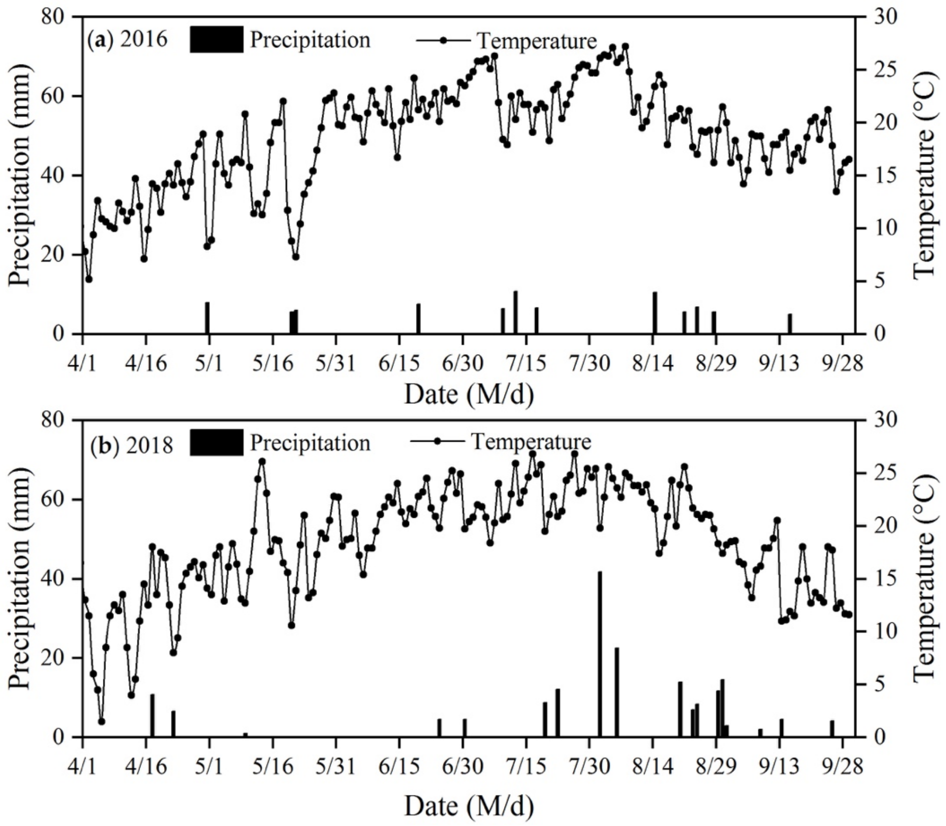

Figure 1. Daily precipitation and average air temperature during the growing season (**a**) in 2016 and (**b**) in 2018 at the Shiyang River Basin Experiment Station, Wuwei City, China.

2.2. Irrigation Treatments and Management Practices

The spring maize variety—XianYu 335—was sown manually in 5 cm deep holes with a row spacing of 40 cm on 28 April in 2016 and 1 May in 2018. Harvest was conducted on 25 September in 2016 and 24 September in 2018, respectively. The plots were over-sown with hand planters and then thinned at the 4-leaf to 86,000 plants ha^{-1}. The experiment consisted of three treatments (W1, W2, W3) which differed in D_h. D_h values in W1, W2 and W3 were set as 0–40 cm, 0–50 cm and 0–60 cm, respectively. Irrigation was applied when the SWC within 0–40 cm soil layer decreased to 60% field capacity (θ_{FC}). The irrigation rate (I, mm) was calculated as follows:

$$I = 10 \times D_h \times (\theta_t - \theta_n) \quad (1)$$

where D_h (cm) in W1, W2 and W3 were taken as 40, 50 and 60, respectively; θ_t (cm^3 cm^{-3}) is the targeted SWC within D_h soil depth, which was set as the field capacity; θ_n (cm^3 cm^{-3}) is the SWC within D_h before irrigation.

There were 9 plots in which three replications were randomly arranged for each treatment. The plot had an area of 36 m^2 (6 m × 6 m). There was a 1 m wide non-irrigated buffer zone between adjacent plots for minimizing the interaction effects between adjacent plots. For all treatments, the large pre-sowing irrigation about 110 mm was applied on 1 April in 2016 and 3 April in 2018. The locally recommended fertilization strategy was adopted in the study for all treatments. Before sowing, each plot received 216 kg N ha^{-1} in the form of urea (N 46%), 238 kg P_2O_5 ha^{-1} in the form of calcium superphosphate (P_2O_5 16%) and 90 kg K_2O ha^{-1} in the form of potassium sulfate (K_2O 50%). The base fertilizer was broadcast over the soil, which was then turned over by plowing to transfer the fertilizer to the subsurface. In addition, the top-dressing of 168 kg N ha^{-1} in the form of urea (N 46%) was applied with flood irrigation at tasseling stage (VT) to ensure adequate N availability throughout the growing seasons.

Border irrigation was applied via carefully constructed water pipes with a diameter of 32 mm. A water flow meter (DN-20, Yongqiang Technologies Co. Ltd., Ningbo, Zhejiang, China) with 0.1 L accuracy was installed to measure the irrigation amount applied. Irrigation timing and amounts for spring maize in 2016 and 2018 are presented in Table 2. The management practices of weed, disease and insects control were carried out uniformly for all the treatments. Weeds were controlled via herbicide application combining hand-hoeing. The control of pest and diseases depended on spraying of insecticides and fungicide.

Table 2. Irrigation timing and amount during the growing season for spring maize in 2016 and 2018.

Year	W1		W2		W3	
	Dates (M/d)	I (mm)	Dates (M/d)	I (mm)	Dates (M/d)	I (mm)
2016	6/10	30	6/10	36	6/15	46
	6/20	36	6/20	45	6/27	47
	7/2	36	7/2	35	7/7	52
	7/18	36	7/24	53	7/29	57
	7/29	38	8/3	44	8/8	58
	8/8	42	8/13	48	9/3	58
	9/3	38	9/3	46	9/15	30
	9/15	30	9/15	30		
	Overall	286	Overall	337	Overall	348
2018	5/31	24	5/31	24	5/31	24
	6/10	31	6/15	41	6/15	54
	6/20	33	6/27	42	6/27	55
	7/7	36	7/12	43	7/12	54
	7/18	37	7/24	43	7/29	55
	8/18	36	9/8	40	9/13	30
	9/13	30	9/13	30		
	Overall	227	Overall	263	Overall	272

Notes: W1, W2 and W3 are the treatments with different D_h (designed wetting depth). D_h values in W1, W2 and W3 are 0–40 cm, 0–50 cm and 0–60 cm, respectively.

2.3. Measurements

2.3.1. Soil Water Content (SWC)

Soil samples for SWC measurements were collected weekly with a soil auger (inner diameter 3.5 cm) at 0.1 m intervals down to 1m in each plot. Some additional measurements were carried out after irrigation or rain events. The sampling points were near the center of each treatment plot. The soil samples were dried in a forced-air oven at 105 °C for 24 h. SWC (cm^3 cm^{-3}) was determined based on the fresh soil mass (FM, g) and the dry soil mass (DM, g) of samples and was calculated as follows:

$$SWC = \frac{FM - DM}{DM} \cdot BD \quad (2)$$

where BD (g cm^{-3}) is soil bulk density (Table 1).

2.3.2. Crop Phenology, Plant Morphology and Photosynthesis

During the growing season, crop phenology was observed on a daily basis and defined according to Ritchie et al. [19]. And the date was recorded when 50% or more of the maize plants in each plot reached the following stages: emergence stage (VE), 6 leaf stage (V6), 12 leaf stage (V12), tasseling stage (VT), silking stage (R1) and physiological maturity stage (R6). The phenology observations are presented in Table 3. From inner row in each plot, three plants were randomly selected to measure the leaf area index (LAI) and the plant height biweekly from V12 to R6 using a ruler (1-mm accuracy) in 2016 and 2018. The leaf area per plant (LA) was calculated as:

$$LA = 0.74 \times \sum_{i=1}^{k} (W_i \times L_i) \tag{3}$$

where i is the i-th of leaf of each plant (i = 1, 2, 3 . . . k); L_i is the length from the base to tip of the i-th leaf; W_i is the width of the widest part of the i-th leaf. The constant 0.74 is the coefficient to account for the shape of maize leaves to calculate leaf area [20,21]. LAI was subsequently calculated as LA divided by the projected area per plant.

Table 3. Phenology of spring maize in 2016 and 2018.

Phenological Stage	2016	2018
	Start Date (M/d)	**Start Date (M/d)**
Emergence (VE)	5/9	5/10
6 leaf stage (V6)	6/3	6/5
12 leaf stage (V12)	7/12	7/10
Tasseling (VT)	7/20	7/18
Silking (R1)	7/27	7/28
Physiological Maturity (R6)	9/18	9/20

Notes: V and R are vegetative and reproductive stage, respectively.

In 2016, prior to the measurement of leaf area, the net photosynthesis rate (Pn), transpiration rate (Tr) and the stomatal conductance (Gs) of leaves on the three selected plants in each plot were measured with an LI-6400 portable photosynthesis systems (Li-Cor, Inc., Lincoln, NE, USA). Measurement was done between 9:00 a.m. and 11:00 a.m. at one day before and three days after the irrigation which was applied on 3 September. The same solar light direction was maintained constant for each measurement. The intrinsic water use efficiency (WUE_i) of leaf was defined as Pn/Tr.

2.3.3. Shoot Dry Matter and Grain Yield

To measure the final shoot dry matter, ten plants per plot were selected randomly at harvest, clipped above soil surface and then were air-dried at 75 °C until constant weight was achieved. The grain yield in each treatment was determined by weighting grains (with about 14% moisture content) from the ten plants after natural drying. The results were then converted to t ha^{-1}.

2.3.4. Root Length Density (RLD)

Three plants were randomly selected to collect roots samples by the evacuation method in each plot on 2 September 2016 and 4 September 2018. Each sampling area was 0.3 m in length (perpendicular to the rows) and 0.4 m in width (parallel to the rows). Each cubic soil sample was then vertically divided into ten sections at 0.1 m intervals down to 1m depth. The soil samples containing roots were transferred into a nylon bag with 0.25 mm^2 mesh sieve and soaked in water for 12 h. Subsequently, roots were extracted by gently washing of soil samples with flowing tap water. Meanwhile, the impurities including dead roots were removed. The 2-dimensional root images, which were achieved using a root scanner (Epson Perfection V700 photo, Seiko Epson Crop., Jakarta Selatan, Indonesia) for grey-scale scanning, were used to determine root length via the software WinRHIZO (Vision Pro 5.0a, Regent Instrument Inc., Quebec City Canada). In certain sampling, RLD (cm cm^{-3}) was expressed as the total root length (cm) divided by volume of sampling (cm^3).

2.4. Data Analysis and Calculation

2.4.1. Evapotranspiration (ET) and WUE

Seasonal ET (mm) was calculated as follows [22]:

$$ET = P + I + \Delta SWS - D - R \quad (4)$$

where P (mm) and I (mm) are the total precipitation and irrigation amount from sowing to maturity, respectively; D (mm) is the downward drainage out of root zone, can be ignored due to the low SWC less than field capacity in root zone throughout growing season; R (mm) is the runoff, can be assumed to be zero since the precipitation is not intensive and the experimental plot is flat. The Equation (4) can be simplified to Equation (5).

$$ET = P + I + \Delta SWS \quad (5)$$

ΔSWS is the soil water consumption (mm), was calculated by Equation (6).

$$\Delta SWS = SWS_{sowing} - SWS_{maturity} \quad (6)$$

where SWS_{sowing} and $SWS_{maturity}$ are the SWS at sowing and maturity in 0–1 m soil layer, respectively. WUE (kg m^{-3}) was defined as Equation (7).

$$WUE = \frac{Y}{ET} \quad (7)$$

where Y is grain yield (kg ha^{-1}) and ET is seasonal evapotranspiration (mm).

2.4.2. Available Water Content (AWC) and Total Available Water Content (TAW)

AWC (mm) was calculated as:

$$AWC_i = 10 \times (\theta_i - \theta_{wp,i}) \times D_i \quad (8)$$

where AWC_i is available water content in i-th layer. θ_i and $\theta_{wp,i}$ (cm^3 cm^{-3}) are the SWC and wilting point in the i-th layer, respectively. D_i (cm) is thickness of the i-th layer. i is the soil layer number (*i* = 1, 2, 3 refers to soil layer 0−40 cm, 40−70 cm and 70−100 cm, respectively). The total available water content (TAW) in i-th layer was calculated by Equation (8) in which θ_i was set as field capacity.

2.4.3. Statistical Analysis

For each experimental year, the one-way ANOVA was used to evaluate the effects of the irrigation treatments on the observed parameters. Post-hoc comparisons among treatment means were done by Duncan's test at a 0.05 probability level, which were calculated using SPSS 20.0 statistical software (SPSS Inc., Chicago, IL, USA). All figures were created using OriginPro (OriginLab Corp. Released v.2018).

3. Results

3.1. Soil Available Water Content

The available water content (AWC) at intervals of 0−40, 40−70, 70−100 cm depths were measured in both seasons (Figure 2). For all treatments, similar AWC were observed in 0–40 cm layer in either season. In 40–70 cm and 70–100 cm layers, AWC in W1 was different from other treatments and W1 achieved lowest value at RS in both years. The AWC in root zone (0–100 cm) in W1 was generally smaller than other treatments and less than 0.45TAW at RS in 2016 and 2018. Furthermore, the AWC in root zone for W2 and W3 were also less than 0.45TAW at some points during growing season.

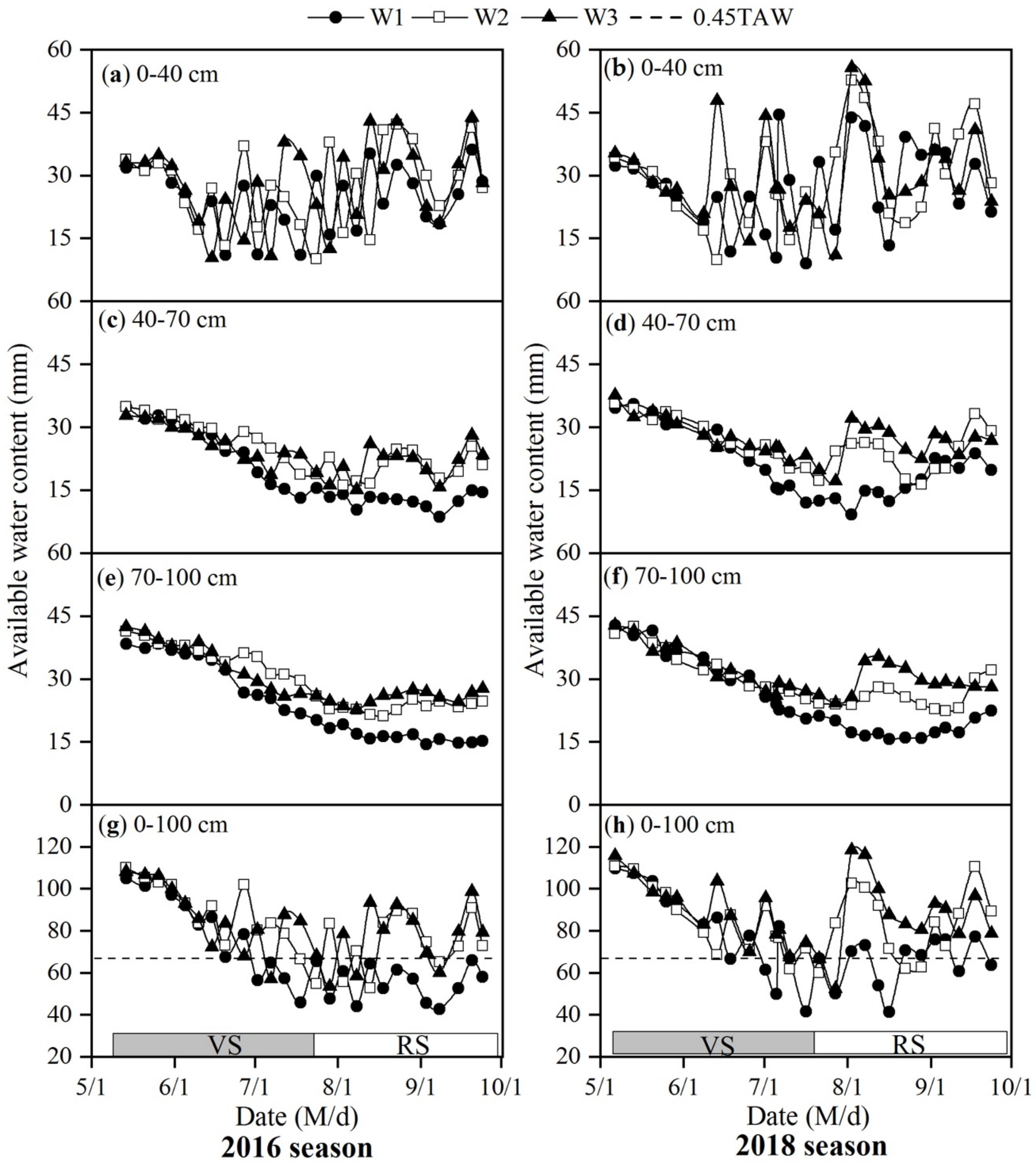

Figure 2. Available water content at soil layers of 0–40 cm (**a**,**b**), 40–70 cm (**c**,**d**), 70–100 cm (**e**,**f**) and 0–100 cm (**g**,**h**) for W1, W2 and W3 in 2016 (left panel) and 2018 (right panel). W1, W2 and W3 are the treatments with different D_h (designed wetting depth). D_h values in W1, W2 and W3 are 0–40 cm, 0–50 cm and 0–60 cm, respectively. Data points indicate average of three replications of one treatment at one point during growing season. VS and RS are vegetative stage and reproductive stage, respectively.

3.2. Root Length Density (RLD)

The results show that roots mainly grew in the upper soil layer (0−40 cm) and declined with soil depth (Figure 3). In 0–40 cm layer, RLD followed the sequence of W3>W2>W1, with RLD of W1 significantly less than either W2 or W3. However, in 70–100 cm layer, the RLD of W1 was significantly higher than either W2 or W3 and there were not significant differences in RLD between W2 and W3 in either season. No significant differences in RLD in 40–70 cm layer among treatments were observed.

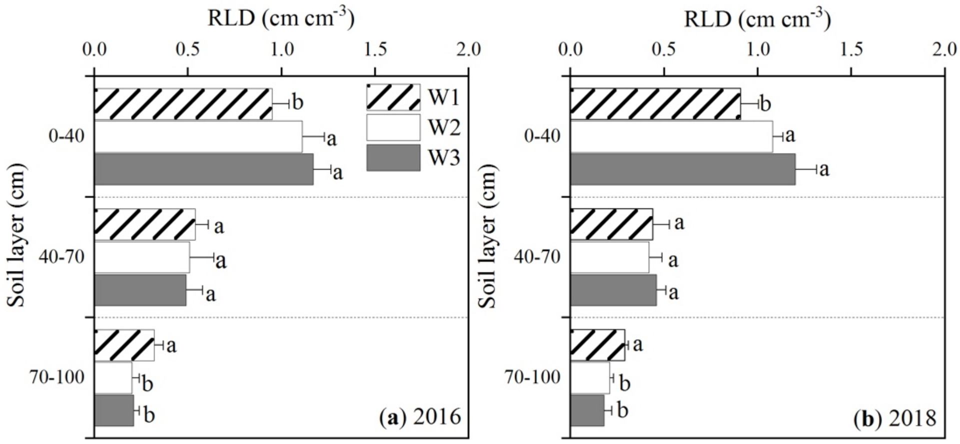

Figure 3. Root length density (RLD) for 0–40 cm, 40–70 cm and 70–100 cm soil layers (**a**) in 2016 and (**b**) in 2018. W1, W2 and W3 are the treatments with different D_h (designed wetting depth). D_h values in W1, W2 and W3 are 0–40 cm, 0–50 cm and 0–60 cm, respectively. Horizontal bars represent standard errors. Different letters above bar plot indicate that there are significant differences in RLD between means for a specified soil layer ($P < 0.05$).

3.3. Leaf Area Index (LAI) and Plant Height

The temporal changes in LAI and plant height were tracked throughout the growing season (Figure 4). Plants reached the maximum LAI at the silking stage at all treatments. LAI followed the sequence of W3 > W2 > W1 and the maximum LAI in W1 was significantly lower than in W3 in both years. No significant differences in plant height among treatments were observed in either season. The mean maximum plant height across the two years was 287, 303 and 310 cm for W1, W2 and W3, respectively.

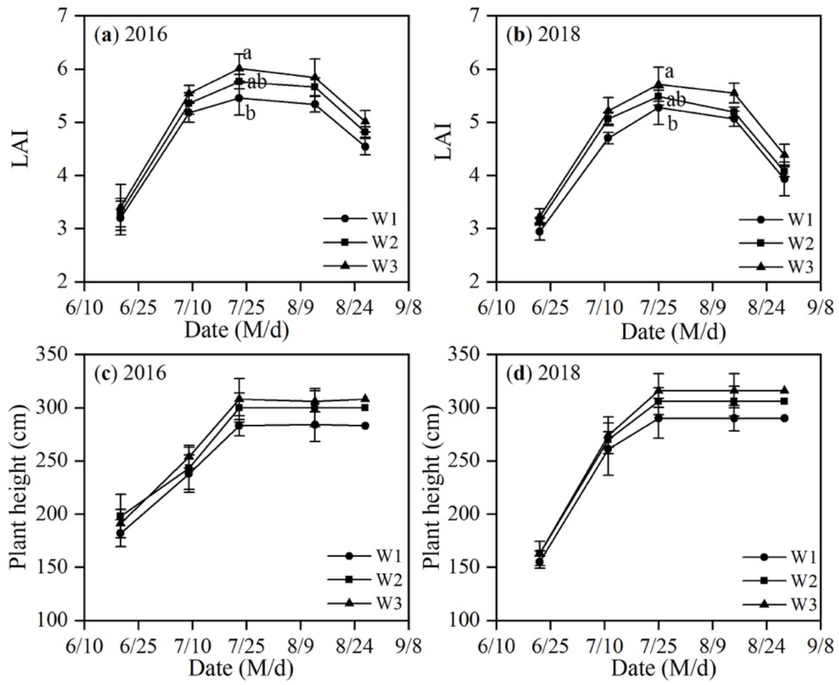

Figure 4. Temporal changes in leaf area index (LAI) (**a**,**b**) and plant height (**c**,**d**) due to W1, W2 and W3 (**a**,**c**) in 2016 and (**b**,**d**) in 2018. W1, W2 and W3 are the treatments with different D_h (designed wetting depth). D_h values in W1, W2 and W3 are 0–40 cm, 0–50 cm and 0–60 cm, respectively. Vertical bars represent standard errors. Different letters above bar plot indicate that there are significant differences in maximum LAI among treatments ($P < 0.05$).

3.4. Photosynthesis

Net photosynthesis rate (Pn), transpiration rate (Tr), stomatal conductance (Gs) and intrinsic water use efficiency (WUE_i) of spring maize before (BI) and after (AI) irrigation are shown in Figure 5. Compared to BI, the Pn, Tr and Gs of AI were greater while WUE_i of AI was smaller, for all treatments. Before irrigation event, W3 exhibited the highest Tr, Gs and Pn among treatments and the Gs and Tr of W1 were significantly lower than either W2 or W3. However, the WUE_i of BI was highest in W1 and significantly higher than in other treatments. After irrigation event, there were no differences in Tr, Gs and WUE_i among all treatments. Moreover, no significant differences of Pn among all treatments were observed before and after irrigation event. The mean values of Gs and Tr followed the sequence of W3 > W2 > W1 and for W1 were markedly lower than for W3. Interestingly, significant differences in mean value of Pn among treatments were not observed. The mean value of WUE_i in W1 was significantly higher than in either W2 or W3.

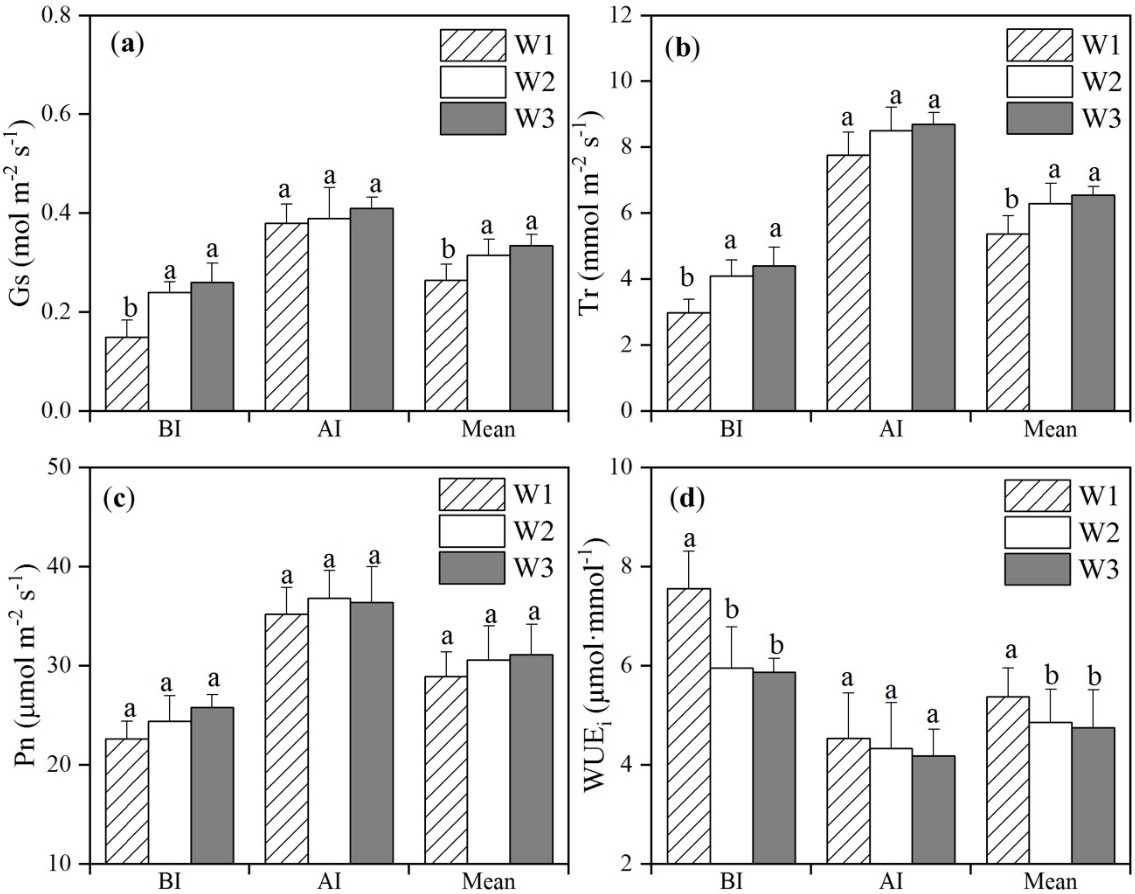

Figure 5. Stomatal conductance (Gs) (**a**), transpiration rate (Tr) (**b**), net photosynthesis rate (Pn) (**c**) and intrinsic water use efficiency (WUE_i) (**d**) of spring maize before (BI) and after (AI) irrigation in 2016. Mean values indicate the average values from BI and AI. W1, W2 and W3 are the treatments with different D_h (designed wetting depth). D_h values in W1, W2 and W3 are 0–40 cm, 0–50 cm and 0–60 cm, respectively. Vertical bars represent standard errors. Different letters above bar plot indicate that there are significant differences in Pn/Tr/Gs among treatments at $P < 0.05$.

3.5. Shoot Dry Matter, Grain Yield and Water Productivity

The crop water consumption (ET) increased with the increasing of irrigation amount (Table 2) and there were large differences in ET among three treatments for both years (Table 4). W1 consumed the least amount of irrigation water and W3 consumed the highest amount (Table 2). Significant differences in shoot dry matter and grain yield were not found among treatments in either year. The

WUE followed the order of W1>W2>W3 and W1 had significantly higher WUE than W3 in 2016 and 2018.

Table 4. Final shoot dry matter (SDM), grain yield (GY), actual crop water consumption (ET) and water use efficiency (WUE) of spring maize under irrigation treatments in 2016 and 2018.

Year	Treatment	SDM (t ha^{-1})	GY (t ha^{-1})	ET (mm)	WUE (kg m^{-3})
2016	W1	25.7 **a**	13.3 **a**	476	2.79 **a**
	W2	26.5 **a**	13.9 **a**	544	2.55 **ab**
	W3	27.2 **a**	14.3 **a**	606	2.36 **b**
2018	W1	25.1 **a**	13.1 **a**	482	2.72 **a**
	W2	25.9 **a**	13.6 **a**	550	2.47 **b**
	W3	26.6 **a**	14.0 **a**	585	2.39 **b**

Notes: W1, W2 and W3 are the treatments with different D_h (designed wetting depth). D_h values in W1, W2 and W3 are 0–40 cm, 0–50 cm and 0–60 cm, respectively. Treatments having different letters indicate significant differences at $P < 0.05$.

4. Discussion

Pre-sowing irrigation is important for water saving and high yield under irrigation strategies in this study. Yan et al. [23] have reported that SWC before sowing played an important role in seedling emergence rate and the following growth of maize. Below field capacity, the greater SWC leads to a greater emergence rate of maize [24]. Soil water before sowing is a key factor in determining a high and stable grain yield in dry years [25]. The pre-sowing irrigation is favorable to the improvement of WUE and grain yield under limited irrigation strategies [26,27]. Additionally, the pre-sowing irrigation replenished the soil water in subsoil, which guaranteed the development of the root system in deficit irrigation regimes. The adequate water in the subsoil plays an important role in inducing deeper rooting such that the absorption of water and nutrition from subsoil is enhanced [28].

The D_h varied by 10 cm among W1, W2 and W3 for each development stage. The SWC in 0–40 cm was regulated by irrigation and maintained a relatively high level (>60% θ_{FC}) during the whole growing season. The marked differences in AWC were observed in 40–70 cm and 70–100 cm at RS (Figure 2), which was mainly attributed to the differences in replenishment of soil water by irrigation among treatments. The lowest AWC in the root zone (0–100 cm) was observed in W1 and was less than 0.45 TAW at RS. According to Djaman et al. [29] and Payero et al. [30], maize will experience soil water stress if AWC in the root zone is less than 0.45 TAW. This indicated that all treatments experienced water stress at RS and W1 suffered more severe water stress. W1 with lowest irrigation amount had the highest RLD in 70–100 cm among treatments (Figure 3), as found by Panda et al. [31] who reported that limited irrigation is beneficial to increase RLD in deeper layers and enhances the absorption of soil water. As a result, the lowest AWC in 70–100 cm was achieved in W1. However, this finding contradicted the earlier report of Farré and Faci [28] who showed that plant roots develop better and can absorb more water from lower soil layers under less soil water stress. According to Li et al. [32], the utilization of soil water in subsoil contributes to the improvement of WUE. Similarly, W1 had the higher WUE compared to W2 and W3 in the study (Table 4). Our study indicated that the plant height and LAI of the crop decreased with the reduction of irrigation amount. The maximum LAI in W1 was significantly lower than in W3 while no significant differences in plant height among three treatments were observed in both years (Figure 4), meaning leaf area was more sensitive to water deficit than plant height. This was consistent with previous research that showed leaf expansion is usually affected by soil water stress firstly and there are not significant relations between soil water deficit and plant height of maize [15,28,29]. In addition, the lower LAI in W1 relative to W2 and W3 is an influencing factor to W1 achieving lower ET [22].

Grain yields obtained in W1, W2 and W3 were comparable to the typical yield under full irrigation in the local area (14.3 t ha^{-1}) reported by Hu et al. [6]. This indicates that it was adequate for achieving high grain yield to maintain SWC in 0–40 cm layer above 60% θ_{FC} with not replenishing soil water in

40–100 cm layer during growth season. Ahmadi et al. [12] have showed that more than 65% of the total maize water consumption is supplied by the top 0.45 m of the root zone. Soil water absorbed from the top 40 cm layer probably provided adequate water for crop photosynthesis, as can be seen from the comparatively high net photosynthesis (Figure 5) observed in this study. Similarly, Fang et al. [33] found that acceptable grain yield of maize can be achieved by maintaining SWC in 0–50 cm layer at 50% to 60% θ_{FC} in North China. The highest WUE was achieved in W1 and was 13% more than the typical regional level of 2.46 kg m^{-3} reported by Hu et al. [6]. This can be attributed to the water stress occurred in W1. Under soil water stress, the crop would down-regulate stomata opening to adapt to drought [34]. Gs is reduced due to the narrowing of stomatal aperture [35]. The reduced Gs (Figure 5) led to reduced transpiration. Nonetheless, the photosynthesis was not proportionally reduced as Gs due to less sensitivity of photosynthesis than Gs. This was also found by Kang and Zhang [34], who found that a small narrowing of stomata opening can significantly reduce water loss (transpiration) with little effect on photosynthesis under deficit or partial root drying irrigation conditions. As a result, W1 had the highest WUE_i among three treatments (Figure 5). Besides, the mild water stress can regulate the partitioning of dry matter, with more dry matter allocated to grain, which is beneficial to higher WUE [36].

In the study, W1 was claimed as optimal supplemental irrigation strategy due to the highest WUE in W1. The positive effect of enhancing WUE on sustainable crop production in the arid and semi-arid region is enormous, which should be considered in a broader scope (e.g., watershed, basin, irrigation district or catchment) than experimental field [37–39]. In W1, the WUE was significantly higher than in W3, although the grain yield had a slight decline of less than 7% compared to that in W3. This means that more water is saved and reallocated to cultivation of other farmlands to achieve additional yielding. Improving WUE has been considered to be the best way to improve crop yield in semi-arid region [40]. In the optimal supplemental irrigation strategy, the value of D_h is 40 cm which is lower limit for the trial range of D_h in the study. It is possible that higher WUE is obtained by applying smaller D_h (<40 cm) in the limited supplemental irrigation strategy. However, the smaller D_h may result in higher frequency irrigation which is usually time-consuming and costly. Meanwhile, more soil evaporation may be caused by increased irrigation frequency [41]. These speculations will be taken into account in future studies.

Applying high quota irrigation (90 mm or even more) in each irrigation event during growth season is also found in maize production in other locations or countries [42,43]. We hope our findings can contribute to the development of water-saving agriculture in a greater scope. The limitation to extensive applicability of the optimal irrigation strategy in the study is the uncertainty of soil water condition in lower part of root zone (40–100 cm) under the irrigation strategy. The severe water deficit in the lower part of root zone (LPR) should be prevented [44]. The soil water in LPR only is replenished before sowing and is not regulated by irrigation during growing season under the optimal irrigation strategy. The soil water condition in LPR during growing season is affected by absorption of crops and unpredictable rainfall. These influence factors vary with locations. The little precipitation (<160 mm) and high reference evapotranspiration (>540 mm) [45] in the experimental location during the long growth season of maize (>150 days) prompt the utilization of soil water in LPR. However, in the study, the negative effect of soil water condition in LPR on yield and WUE was not observed under high consumption with low replenishment of soil water in LPR. The good performance of the optimal irrigation strategy under the harsh environmental conditions in the study means the only replenishment of soil water in LPR before sowing is enough for preventing severe water deficit in the LPR with strong possibility. As a result, the optimal irrigation strategy can be applied in more locations or countries besides the northwest China.

5. Conclusions

In the study, three treatments with different D_h had similar grain yields while there were significant differences in WUE among treatments. The highest WUE was achieved in W1 which suffered mild water stress. The optimal supplemental irrigation strategy, which only replenished soil water in top 40 cm to maintain SWC in this soil layer above 60% θ_{FC} based on sufficient pre-sowing soil water level, is recommended for maize production in arid regions. Compared to typical WUE and grain yield values in the local area, the WUE was improved by 13% and the grain yield was comparable under optimal irrigation strategy. Water drainage caused by pre-sowing irrigation should be reduced as far as possible. A pre-sowing irrigation which replenishes soil water content in soil profile of 0–1 m to field capacity is enough. In the optimal supplemental irrigation strategy, irrigation timing and water application depth was determined based on soil water status in 0–40 cm layer. It is not necessary for local farmers to monitor soil water status in the lower part of root zone.

Author Contributions: S.Z., X.H. and Z.Z. improved the conceptualization and designed field experiments; S.Z. and X.H. collected and analyzed the data; the writing—first draft was carried out by Z.S.; H.R. and W.W. read the manuscript and provided important advice about methodology which contributed to improvement of the manuscript.

Funding: Our research was funded by Natural Science Foundation of China (No.51179163) and the Special Fund for Research in the Public Interest (No.201503125).

Acknowledgments: We would like to thank the staff of the Wuwei Experimental Station, China Agricultural University for their valuable help during the experiments.

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

References

1. Xie, Z.K.; Wang, Y.J.; Li, F.M. Effect of plastic mulching on soil water use and spring wheat yield in arid region of northwest China. *Agric. Water Manag.* **2005**, *75*, 71–83. [CrossRef]
2. Du, T.S.; Kang, S.Z.; Zhang, X.Y.; Zhang, J.H. China's food security is threatened by the unsustainable use of water resources in North and Northwest China. *Food Energy Secur.* **2014**, *3*, 7–18. [CrossRef]
3. Kang, S.Z.; Su, X.L.; Tong, L.; Zhang, J.H.; Zhang, L.; Davies, W.J. A warning from an ancient oasis: Intensive human activities are leading to potential ecological and social catastrophe. *Int. J. Sustain. Dev. World* **2008**, *15*, 440–447. [CrossRef]
4. Wang, F.X. Experimental Study on Sowing with Water of Absolved Water-Storing Irrigation Technology on Maize in Inland Irrigation District of Hexi. Master's Thesis, Gansu Agricultural University, Lanzhou, China, 2009. (In Chinese with English abstract).
5. Wang, S.H.; Wang, Y.B.; Ding, L.; Zhao, L. Experimental study on water storage irrigation in spring for wheat and corn in Huangyang irrigation district. *GanSu Water Resour. Hydropower Technol.* **2013**, *49*, 14–17. (In Chinese)
6. Hu, Z.Q.; Ma, Z.M.; Bao, X.G.; Zhang, J.D. Effect of RDI on Yield and Water Consumption of Major Crops in Shiyang River Area. *Water Sav. Irrig.* **2010**, *7*, 10–13. (In Chinese with English abstract).
7. Ding, R.S.; Kang, S.Z.; Li, F.S.; Zhang, Y.Q.; Ling, T.; Sun, Q.Y. Evaluating eddy covariance method by large-scale weighing lysimeter in a maize field of northwest china. *Agric. Water Manag.* **2010**, *98*, 87–95. [CrossRef]
8. Qin, S.J.; Kang, S.Z.; Du, T.S.; Tong, L.; Ding, R.S. Can the drip irrigation under film mulch reduce crop evapotranspiration and save water under the sufficient irrigation condition? *Agric. Water Manag.* **2016**, *177*, 128–137. [CrossRef]
9. Zhang, B.Z.; Yin, G.X.; Zhang, X. Determination of Several Water-saving Irrigation Indicators for Wheat and Corn with High Yield in Guanzhong Irrigated Region. *Bull. Soil Water Conserv.* **2009**, *29*, 142–145. (In Chinese with English abstract).
10. Fang, Q.X.; Ma, L.W.; Yu, Q.; Ahuja, L.R.; Malone, R.W.; Hoogenboom, G. Irrigation strategies to improve the water use efficiency of wheat–maize double cropping systems in North China Plain. *Agric. Water Manag.* **2010**, *97*, 1165–1174. [CrossRef]
11. Yu, G.R.; Zhuang, J.; Nakayama, K.; Jin, Y. Root water uptake and profile soil water as affected by vertical root distribution. *Plant Ecol.* **2007**, *189*, 15–30. [CrossRef]

12. Ahmadi, S.H.; Mosallaeepour, E.; Kamgar-Haghighi, A.A.; Sepaskhah, A.R. Modeling Maize Yield and Soil Water Content with AquaCrop under Full and Deficit Irrigation Managements. *Water Resour. Manag.* **2015**, *29*, 2837–2853. [CrossRef]
13. Passioura, J. Increasing crop productivity when water is scarce-from breeding to field management. *Agric. Water Manag.* **2006**, *80*, 176–196. [CrossRef]
14. Zuo, Q.; Shi, J.; Li, Y.; Zhang, R. Root length density and water uptake distributions of winter wheat under sub-irrigation. *Plant Soil* **2006**, *285*, 45–55. [CrossRef]
15. Greaves, G.E.; Wang, Y.M. Effect of regulated deficit irrigation scheduling on water use of corn in southern Taiwan tropical environment. *Agric. Water Manag.* **2017**, *188*, 115–125. [CrossRef]
16. Du, T.S.; Kang, S.Z.; Zhang, J.H.; Davies, W.J. Deficit irrigation and sustainable water-resource strategies in agriculture for China's food security. *J. Exp. Bot.* **2015**, *66*, 2253–2269. [CrossRef] [PubMed]
17. Kang, S.Z.; Hu, X.T.; Cai, H.J.; Feng, S.Y. New ideas and development tendency of theory for water saving in modern agriculture and ecology. *J. Hydraul. Eng.* **2004**, *35*, 1–7. (In Chinese with English abstract).
18. Heng, T.; Liao, R.K.; Wang, Z.H.; Wu, W.Y.; Li, W.H.; Zhang, J.Z. Effects of combined drip irrigation and sub-surface pipe drainage on water and salt transport of saline-alkali soil in Xinjiang, China. *J. Arid Land* **2018**, *10*, 932–945. [CrossRef]
19. Ritchie, S.W.; Hanway, J.J. *How a Corn Plant Develops*; Iowa State Univ: Ames, IA, USA, 1992.
20. Ding, R.S.; Tong, L.; Li, F.S.; Zhang, Y.Q.; Hao, X.M.; Kang, S.Z. Variations of crop coefficient and its influencing factors in an arid advective cropland of northwest china. *Hydrol. Process.* **2015**, *29*, 239–249. [CrossRef]
21. Li, S.E.; Kang, S.Z.; Li, F.S.; Zhang, L. Evapotranspiration and crop coefficient of spring maize with plastic mulch using eddy covariance in northwest China. *Agric. Water Manag.* **2008**, *95*, 1214–1222. [CrossRef]
22. Karam, F.; Breidy, J.; Stephan, C.; Rouphael, J. Evapotranspiration, yield and water use efficiency of drip irrigated corn in the Bekaa Valley of Lebanon. *Agric. Water Manag.* **2003**, *63*, 125–137. [CrossRef]
23. Yan, Z.X.; Gao, C.; Ren, Y.J.; Zong, R.; Ma, Y.Z.; Li, Q.Q. 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.* **2017**, *186*, 21–28. [CrossRef]
24. Ma, S.Q.; Wang, Q.; Lv, H.Q.; Xu, L.P.; Yu, H.; Zhang, T.L. Impact of water and temperature on spring maize emergence speed and emergence rate. *Acta Ecologica Sinica* **2012**, *32*, 3378–3385. (In Chinese with English abstract).
25. Ma, L.; Trout, T.J.; Ahuja, L.R.; Bausch, W.C.; Saseendran, S.A.; Malone, R.W.; Nielsen, D.C. Calibrating RZWQM2 model for maize responses to deficit irrigation. *Agric. Water Manag.* **2012**, *103*, 140–149. [CrossRef]
26. Schlegel, A.J.; Stone, L.R.; Dumler, T.J.; Lamm, F.R. Managing diminished irrigation capacity with preseason irrigation and plant density for crop production. *Trans. ASABE* **2012**, *55*, 525–531. [CrossRef]
27. Kisekka, I.; Schlegel, A.; Ma, L.; Gowda, P.H.; Prasad, P.V.V. Optimizing preplant irrigation for maize under limited water in the High Plains. *Agric. Water Manag.* **2017**, *187*, 154–163. [CrossRef]
28. Farré, I.; Faci, J.M. Deficit irrigation in maize for reducing agricultural water use in a Mediterranean environment. *Agric. Water Manag.* **2009**, *96*, 383–394. [CrossRef]
29. Djaman, K.; Irmak, S.; Rathje, W.R.; Martin, D.L.; Eisenhauer, D.E. Maize evapotranspiration, yield production functions, biomass, grain yield, harvest index, and yield response factors under full and limited irrigation. *Am. Soc. Agric. Biol. Eng.* **2013**, *56*, 273–293.
30. Payero, J.O.; Tarkalson, D.D.; Irmak, S.; Davison, D.; Petersen, J.L. Effect of timing of a deficit-irrigation allocation on corn evapotranspiration, yield, water use efficiency and dry mass. *Agric. Water Manag.* **2009**, *96*, 1387–1397. [CrossRef]
31. Panda, R.K.; Behera, S.K.; Kashyap, P.S. Effective management of irrigation water for maize under stressed conditions. *Agric. Water Manag.* **2004**, *66*, 181–203. [CrossRef]
32. Li, Q.; Dong, B.; Qiao, Y.; Liu, M.; Zhang, J. Root growth, available soil water, and water-use efficiency of winter wheat under different irrigation regimes applied at different growth stages in North China. *Agric. Water Manag.* **2010**, *97*, 1676–1682. [CrossRef]
33. Fang, Q.; Ma, L.; Yu, Q.; Malone, R.W.; Saseendran, S.A.; Ahuja, L.R. Modeling Nitrogen and Water Management Effects in a Wheat-Maize Double-Cropping System. *J. Environ. Qual.* **2008**, *37*, 2232–2242. [CrossRef]

34. Kang, S.Z.; Zhang, J.H. Controlled alternate partial root-zone irrigation: Its physiological consequences and impact on water use efficiency. *J. Exp. Bot.* **2004**, *55*, 2437–2446. [CrossRef] [PubMed]
35. Liu, F.L.; Jensen, C.R.; Shahanzari, A.; Andersen, M.N.; Jacobsen, S.E. ABA regulated stomatal control and photosynthetic water use efficiency of potato (*Solanum tuberosum* L.) during progressive soil drying. *Plant Sci.* **2005**, *168*, 831–836. [CrossRef]
36. Dry, P.R.; Loveys, B.R. Factors influencing grapevine vigour and the potential for control with partial root zone drying. *Aust. J. Grape Wine Res.* **2010**, *4*, 140–148. [CrossRef]
37. Deng, X.P.; Shan, L.; Zhang, H.P.; Turner, N.C. Improving agricultural water use efficiency in arid and semiarid areas of China. *Agric. Water Manag.* **2006**, *80*, 23–40. [CrossRef]
38. Zhang, S.L.; Sadras, V.; Chen, X.P.; Zhang, F.S. Water use efficiency of dryland maize in the Loess Plateau of China in response to crop management. *Field Crops Res.* **2014**, *163*, 55–63. [CrossRef]
39. Howell, T.A. Enhancing water use efficiency in irrigated agriculture. *Agron. J.* **2001**, *93*, 281–289. [CrossRef]
40. Shan, L.; Chen, G.L. *The Theories and Practices of Dry-land Agriculture in Loess Plateau*; Scientific Publisher: Beijing, China, 1993; pp. 222–229. (In Chinese)
41. Klocke, N.L.; Currie, R.S.; Aiken, R.M. Soil water evaporation and crop residues. *Trans. ASABE* **2009**, *52*, 103–110. [CrossRef]
42. Kuscu, H.; Karasu, A.; Oz, M.; Demir, A.O.; Turgut, I. 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* **2013**, *18*, 13–19.
43. Steele, D.D.; Stegman, E.C.; Knighton, R.E. Irrigation management for corn in the northern Great Plains, USA. *Irrig. Sci.* **2000**, *19*, 107–114. [CrossRef]
44. Wang, F.F.; Zhang, S.P.; Shao, L.J.; Li, G.; Chen, X.L.; Liu, P.; Zhao, B.Q.; Dong, S.T.; Zhang, J.W.; Zhao, B. Effect of Root in Different Soil Layers on Plant Growth and Yield Formation After Anthesis in Summer Maize. *Sci. Agric. Sin.* **2013**, *46*, 4007–4017. (In Chinese with English abstract).
45. Jiang, X.L.; Kang, S.Z.; Tong, L.; Li, F.S.; Li, D.H.; Ding, R.S.; Qiu, R.J. Crop coefficient and evapotranspiration of grain maize modified by planting density in an arid region of northwest china. *Agric. Water Manag.* **2014**, *142*, 135–143. [CrossRef]