Comparison of Deficit Irrigation Management Strategies on Root, Plant Growth and Biomass Productivity of Silage Maize

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Abbreviations

DI: deficit-irrigation; DIM: deficit-irrigation management; ET_{CF} : evapotranspiration of maize grown at field conditions; ET_{CP} : evapotranspiration of maize grown in pots; GDD: growing degree days; I: irrigation; I_1 : severe-deficit-irrigation level; I_2 : moderate-deficit-irrigation level; I_3 : mild-deficit-irrigation level; I_4 : full-irrigation level; IWUE: irrigation water use efficiency; K_C :maize crop coefficient in the field conditions; K_{MC} : microclimate coefficient; K_y : response factor to water stress; LA: leaf area; LAI: leaf area index; MAD: maximum allowable depletion; M_1 : fixed irrigation interval-variable irrigation depth management; M_2 : variable irrigation interval-fixed irrigation depth management; RB: root biomass; RBD: root biomass density; RSR: root:shoot ratio; S: growth stage; S_1 : 10-leaf stage; S_2 :16-leaf stage; S_3 : tasseling stage; S_4 : milk stage; S_5 : silage harvest stage; SWD: soil water depletion; TB: total aboveground biomass; WUE: water use efficiency.

Abstract

Knowledge about biomass partitioning of maize grown in arid and semi-arid climates is scarce and yet essential to select a robust and effective deficit irrigation management (DIM) strategy for these regions. The objectives of this study were to: i) investigate the effects of different levels of water application under two DIM strategies on the root and aboveground characteristics, the response factor to water stress (K_y) and irrigation water use efficiency (IWUE) of silage maize at different growth stages, and ii) determine the best DIM strategy that would maximize biomass productivity. Field pot experiments were conducted in Isfahan, Iran, during 2009 and 2010. The two DIM strategies were fixed irrigation interval-variable irrigation depth (M_1), and variable irrigation interval-fixed irrigation depth (M_2). Each DIM strategy was tested at four water-deficit levels, including: severe, moderate, mild, and a full-irrigation. In M_1 , irrigation intervals were consistent for all irrigation treatments but were varied over the growing season. Treatment effects were measured at the 10-leaf, 16-leaf, tasseling, milk, and silage harvest crop growth stages. There was significant effect of irrigation and growth stage on total aboveground biomass (TB), leaf area (LA), root biomass (RB), and root:shoot ratio (RSR) for both DIM strategies during the two years. For M_2 , there was significant difference in TB, LA, RB, and RSR between all irrigation levels at all growth stages. TB production was on the average around 25% higher for M_1 compared to M_2 , even though total applied irrigation water was only 6% higher for M_1 . Comparing the two DIMs showed that RSR and K_y were both higher for M_2 , indicating that the crop was more sensitive to this strategy. In conclusion, M_1 was selected as the best management practice since it had more favorable effects on improving the IWUE and also on the development of maize roots during the growing season.

Keywords: *Zea mays*, Irrigation interval, Water use efficiency, Growth stage; Water stress.

1.0 Introduction

Water scarcity affects first and foremost the 52% of world's population who live in arid and semi-arid regions (UNESCO-WWAP, 2006). Consequently, there is a mounting pressure to reduce irrigation water use, while sustaining agricultural production in these regions (Dehghanisanij *et al.*, 2009). To optimize crop yield and quality, a robust and effective irrigation management strategy, that is adaptable to these regions, must also be developed and adopted by local farmers. Deficit irrigation (DI) is often a good choice (Gheysari *et al.*, 2015). The idea behind DI is to obtain significant water-savings with only small reduction in crop yield by exposing the crop to mild water stress during its less sensitive growth stages (Costa *et al.*, 2007; Geerts and Raes, 2009). Successful implementation of DI, however, requires knowledge about the crops and management of limited water availability (Farré and Faci, 2009) and how that may change over time, *e.g.*, from season-to-season, from year-to-year.

Irrigation water use efficiency (IWUE) and the response factor to water stress (K_y) are commonly used indices to evaluate the efficacy of DI, and to estimate the thresholds to delivery water and of water stress in order to optimize management decisions (Johnson and Henderson, 2002). IWUE provides actionable data about how to manage and optimize productivity, *i.e.*, effectiveness of irrigation as per some measures of yield and biomass (Sinclair *et al.*, 1984) whereas K_y is used to assess water–yield relationships *i.e.*, the linear slope between water stress and yield (or biomass) over time.

Maize accounts for one-fourth of annual global cereal harvest (FAO, 2000). It is also the most geographically ubiquitous crop with the most extensive cultivation occurring from approximately 50°N to 45°S (Leff *et al.*, 2004). Iran, with an arid and semi-arid climate (average annual precipitation of 251 mm) is located in this latitudinal range and recognizes maize as a major summer silage crop, particularly in the central parts of the country

(Gheysari *et al.*, 2009a). Total maize biomass production in Iran is often as important to farmers as grain, since animals are a significant part of their livelihood. As water becomes scarcer, however, local farmers need to improve DI management strategies to optimize crop production and profits.

Several studies (Oktem, 2008; Ko and Piccinni, 2009; Ayana, 2011; Domínguez *et al.*, 2012 and many others) have investigated the effect of DI on IWUE and K_y of maize. A relatively wide range has been reported for both factors (*i.e.*, 0.85 to 8.64 kg m⁻³ for IWUE and 0.76 to 1.5 for K_y , cf. Gheysari *et al.*, 2015) depending on depth and frequency of irrigation, type of irrigation system, plant density and cropping system, nitrogen application strategies, soil management practices as well as climate and microclimate conditions (Grassini *et al.*, 2011). Moreover, several studies have also shown that applying DI strategy during the vegetative growth stage of maize affects both above- and below-ground crop development. For example, DI has been found to decrease aboveground biomass, such as leaf area (Lizaso *et al.*, 2001), leaf and stem weight (Pandey *et al.*, 2000) and total biomass (Dadgelen *et al.*, 2006; Gheysari *et al.*, 2009a). On the other hand, it has been reported to increase below-ground biomass, such as root:shoot ratio (Kanget *et al.*, 1998; Bonifas *et al.*, 2005) and root dry matter production (Oktem, 2008; Sangakkara *et al.*, 2010).

Most (above) studies have focused on conditions of severe water stress. Nevertheless, the effects of moderate water stress on maize, which is more likely to occur in practice under arid and semi arid regions have been less evaluated (Farre and Faci, 2009). In addition, no research has been carried out that has “simultaneously” investigated the effects of different DI strategies on the root and aboveground biomass production of silage maize in arid or semi-arid regions. There is inaction among most maize growers (particularly those in Iran) about how to apply the knowledge from studies on decreasing the depth or frequency of irrigation on biomass productivity. This is due, in part, because growers that may wish to implement

deficit irrigation management (DIM) do not know how to judge the potential associated risk in the reduction of yield (Farre and Faci, 2006).

Estimates of maize biomass production under DI are also needed to i) understand the competition between crops and weeds (cf. Muchow and Davis, 1988; Semere and Froud-Williams, 2001), ii) model productivity based on the intercepted photosynthetically active radiation (IPAR) (cf. Andrade, 1995), and iii) inform plant allocation models that intend to determine carbon inputs to the soil in efforts to mitigate greenhouse effects (Gale *et al.*, 2001; Verma *et al.*, 2005). Estimates of maize production are often reported as root:shoot ratio (RSR) in efforts to understand plant allocation patterns, *i.e.*, distinguish between root (RB) and shoot biomass. However, the labor-intensive nature of root sampling and the wide variety of sampling techniques (with multiple sources of quantified uncertainty) have led to a paucity of maize RB data in the literature, and only a few researchers have endeavored to characterize the RSR throughout an entire growing season (Amos and Walters, 2006).

The objectives of this study were to: 1) investigate the effects of different levels of water application under two common deficit irrigation management strategies on the root and aboveground characteristics of silage maize (Hybrid 704 singlecross) grown in an arid region, 2) evaluate IWUE and K_y under each of the two DIMs, and 3) determine the optimal DI management strategy for the area under the study.

2. Materials and Methods

2.1. Description of experimental site

This study was conducted at the Agricultural Research Field of Isfahan University of Technology, Isfahan, located in the central part of Iran (51°28' E Long, 32°42' N Lat, 1624 m.a.s.l.) in 2009 and 2010. The area is located in a dry region (according to the Köppen Climate Classification System) with an average annual temperature of 17°C, annual precipitation of 122 mm with no rain in summer. Average monthly temperature ranged from

3.5°C to 40.9°C in 2009 and 3.6°C to 40.8°C in 2010, with the lowest temperature occurring in November and the highest in July. Average annual relative humidity (RH) was 38%, ranging from 13 to 47% in 2009 and 12.5 to 46% in 2010 (Figure 1).

The study was conducted according to a split-split plot experiment using a completely randomized block design with three replications. The experimental treatments consisted of two deficit-irrigation management (DIM) strategies (main plot) applied at five different crop growth stages (sub plot) with four irrigation levels (sub sub plot), which consisted of a total of 120 black polyethylene pots (60 pots for each DIM strategy = 4 irrigation levels $\times$ 5 growth stages $\times$ 3 replications). Each pot had a volume of 98 L, a diameter of 39.4 cm and a height of 80 cm. The selected depth of pot was 60 cm, in accordance with Kang et al. (2002). An additional 10 reserve pots were included, which were used for the substitution of unhealthy plants and for soil sampling. A total of 20 drain holes (3 mm each) were made at the bottom of each pot. Excess water was quickly drained from the experimental site by drainage channels without influencing the water content inside the pots.

The pots were filled with a clay loam soil containing 33% clay, 41% silt and 26% sand in 2009 and 28% clay, 34% silt and 38% sand in 2010. Electrical conductivity (EC) of the soil was 1.9 dSm⁻¹ in 2009 and 1.8 dSm⁻¹ in 2010. The pH was 7.6 and 7.9 in 2009 and 2010, respectively. Bulk density was 1.28 gcm⁻³ in 2009 and 1.41 gcm⁻³ in 2010, measured after three heavy irrigations. The soil in each pot was saturated several times prior to planting the seeds, to create structural uniformity in the soil. The pots were arranged in a square pattern (0.4 $\times$ 0.4 m) to simulate a population of 62,500 plants per hectare (p ha⁻¹), which was within the range of common planting densities for maize in Iran (Gheysari *et al.*, 2009a,b). All potted plants were grown outside under natural environment (light, humidity and temperature regimes), while water (irrigation) was manipulated.

The interstitial space between the pots was covered with white foam sheets (Isfahan Foam Co., Iran) to avoid potential effects of isolation and undue surface heating on root development (Gheysari *et al.*, 2010). In addition, the whole experimental plot was surrounded by embankments constructed at the same height as the soil in the pots (*i.e.*, 70 cm) to avoid potential boundary effects. For more precaution, two rows of maize were planted on these embankments to simulate field conditions and microclimate, and were irrigated manually by graduated cylinders. In each pot, three seeds of silage maize (Hybrid 704 singlecross) were planted. Ten days after planting, the best plant in each pot was kept and the others were removed.

Chemical properties of irrigation water were: sodium (Na^+) = 0.21 meq L^{-1} , calcium (Ca^{2+}) = 3 meq L^{-1} , magnesium (Mg^{2+}) = 1.4 meq L^{-1} , potassium (K^+) = 0.06 meq L^{-1} , chloride (Cl^-) = 0.37 meq L^{-1} , bicarbonate (HCO_3^-) = 4.23 meq L^{-1} , EC = 0.48 dS m^{-1} , pH = 7.5, and SAR = 0.14, which were all within the optimum water quality range for irrigating maize (Ayers and Westcot, 1985).

Daily averages of air temperature (T , $^{\circ}\text{C}$), relative humidity (RH, %), incident solar radiation (SRAD, MJ m^{-2}), horizontal wind speed (U , m s^{-1}), and bulk precipitation (BP, mm) were downloaded to calculate daily reference evapotranspiration from the Najafabad station within 30 km of our field site, as part of the Iranian Meteorological Organization (<http://www.weather.ir/>).

2.2. Soil water content measurement

Eight tensiometers (Soilmoisture Equipment Corp., Santa Barbara, CA) were installed in two pots of the full-irrigation level under each DIM treatment to determine soil water content, which was needed to calculate the depth of irrigation water being applied at each growth stage. The tensiometers were installed with their porous cups centered at 15, 25, 35, and 50 cm depths to represent soil water content in the 10-20 cm, 20-30 cm, 30-40 cm

and 40-60 cm soil layers, respectively. Soil water content in the 0-10 cm soil layer was determined by the gravimetric method (Hillel, 1982) every 2-3 days after irrigation. For each year, the suction measured by the tensiometers (in the range of 0-100 kPa) was converted to soil water content using the procedures described by Smajstrla and Harrison (2011). The conversion equations were as follows:

$$\theta_{m(2009)} = -4.97 \ln C + 35.45 \quad (1)$$

$$\theta_{m(2010)} = -6.80 \ln C + 37.76 \quad (2)$$

where, θ_m is gravimetric soil water content and C is the negative pressure (kPa) measured by the tensiometers.

2.3. Irrigation management

All treatments were irrigated similarly with 2-3 days interval (under no stress condition) prior to 28 days after planting (DAP) in 2009 and 32 DAP in 2010. The two irrigation regimes (M_1 and M_2) started after 10-leaf stage during both years.

2.3.1. Fixed irrigation interval-variable irrigation depth (M_1)

All M_1 pots were irrigated at the same time, with different water depths applied to the different irrigation treatments. Initiation of an irrigation event was based on soil water depletion in the crop root zone with maximum allowable depletion (MAD) equal to 50% (Martin *et al.*, 1991; Kiani *et al.*, 2016) as follows:

$$\theta_{MAD=0.50} = \theta_{FC} - (\theta_{FC} - \theta_{WP}) \times 0.5 \quad (3)$$

where, $\theta_{MAD=0.50}$ is the volumetric soil water content when 50% of total available soil water is depleted (fraction), θ_{FC} is the volumetric soil water content at field capacity (fraction) and θ_{WP} is the volumetric soil water content at wilting point (fraction). The volumetric soil water content at FC and at WP were measured by the pressure plate technique as 27.8% and 9%, respectively in 2009, and 23.1% and 8.4%, respectively in 2010.

It is important to note that a “fixed irrigation interval” here does not mean that the irrigation interval under M_1 was invariant over the growing season. Rather, it denotes that irrigation intervals were consistent for all irrigation treatments (I_1 , I_2 , I_3 and I_4) and was varied over the growing season, as can be verified from Figure 2. The irrigation treatments were irrigated when the weighted average of soil water content in the root zone ($\bar{\theta}$) reached $(1 \pm 0.05) \times \theta_{MAD=0.50}$ (i.e., Eq. 4). Irrigation depth for the full irrigation level was determined using Eq. (5).

$$\bar{\theta} = \frac{\sum_{i=1}^5 (\theta_i \times D_i)}{\sum_{i=1}^5 D_i} \quad (4)$$

$$D_{IRM1} = \sum_{i=1}^5 ((\theta_{FC} - \theta_i) \times D_i) \quad (5)$$

where, D_{IRM1} is the net irrigation depth to replenish a fraction of the soil water depletion (SWD) (cm) for the full irrigation treatment, θ_i is the volumetric soil water content before irrigation (fraction, dimensionless; calculated from Eqs. 1 or 2), D_i is the thickness of the soil layer (cm) in which the root zone was located for full-irrigation level (D_i was 10 cm for layers 1, 2, 3, and 4, and 20 cm for layer 5), and i represents the number of soil layers. Irrigation application efficiency was considered to be 100%.

The irrigation levels were allocated to a fraction of SWD (SWD being equal to irrigation depth for full-irrigation level). This was set to $0.55 \times \text{SWD}$ for level I_1 , $0.70 \times \text{SWD}$ for I_2 , $0.85 \times \text{SWD}$ for I_3 , and $1.0 \times \text{SWD}$ for I_4 (Figure 2).

2.3.2. Variable irrigation interval-fixed irrigation depth (M_2)

All pots under treatment M_2 were irrigated with the same water depth; but different irrigation intervals were used for different irrigation treatments. Because tensiometers were only installed at the fully irrigated pots, they could not be used to schedule irrigation for the DI treatments. As such, a soil water depletion (SWD) (considered to be equal to the total crop evapotranspiration between two consecutive irrigation events) for these treatments was estimated from the FAO-PM equation, which involves using the crop coefficient K_C , in

combination with a microclimate coefficient (K_{MC}) (Allen *et al.*, 1998, Snyder *et al.*, 2015). The microclimate coefficient was intentionally applied here because pots were placed on the ground surface and also because the vegetation cover did not fully mimic field conditions.

The K_{MC} was assumed to be equal for all irrigation levels and was calculated as:

$$K_{MC} = \frac{SWD_p}{\sum ET_{CF}} \quad (6)$$

where, SWD_p is soil water depletion (in the full-irrigation treatment) between two consecutive irrigations, and was determined from tensiometer measurements; and $\sum ET_{CF}$ is the cumulative ET_{CF} between two irrigation events. ET_{CF} is the crop evapotranspiration under field conditions (Eq. 7) and was computed using the grass-reference evapotranspiration (ET_o , FAO-56 Penman-Monteith (FPM) approach, Allen *et al.*, 1998) and site-specific maize crop coefficient (K_C , cf. Gheysari *et al.*, 2006) curve:

$$ET_{CF} = ET_o \times K_C \quad (7)$$

We used the daily evapotranspiration of maize at the pots (ET_{CP} , Eq. 8) to determine the irrigation intervals for deficit irrigation treatment, which was derived from both the evapotranspiration of maize at the field conditions (ET_{CF} , Eq. 7) and K_{MC} , which was derived from full irrigation treatment (Eq. 6)

$$ET_{CP} = ET_{CF} \times K_{MC} \quad (8)$$

The irrigation levels I_1 , I_2 , I_3 , and I_4 were applied when cumulative ET_{CP} after each irrigation event reached $D_{t(MAD=0.85)}$, $D_{t(MAD=0.75)}$, $D_{t(MAD=0.65)}$, and $D_{t(MAD=0.50)}$, respectively. D_t values were calculated as:

$$D_{t(MAD=\alpha)} = \sum_{i=1}^5 (\theta_{FC} - \theta_{WP}) \times \alpha \times D_i \quad (9)$$

where, $D_{t(MAD=\alpha)}$, is the maximum depleted water at $MAD = \alpha$ (fraction), with α being 0.5, 0.65, 0.75, and 0.85 for I_4 , I_3 , I_2 and I_1 , respectively. Applied irrigation depths in this strategy for all irrigation levels were essentially the same as those calculated by Eq. 9 for $\alpha=0.5$

(Figure 2). The irrigation application efficiency was assumed to be 100%. Time step for all the above calculations was 24-h.

2.4. Fertilizer management

Fertilizers were applied based on local fertilizer recommendations. Diammonium phosphate (46% phosphate, 18% nitrogen) at a rate of 92 kg ha⁻¹ and potassium sulphate (50% potassium) at a rate of 81 kg ha⁻¹ were mixed with soil manually to the depth of 25 cm. Urea fertilizer (46% nitrogen) at a total rate of 150 kg N ha⁻¹ was also applied with irrigation water (fertigation) four times at the first irrigation event, and at 30 DAP, 59 DAP, and 74 DAP (Figure 2).

2.5. Crop response measurements

2.5.1. Aboveground crop development

Variables representing aboveground crop development were sampled at different physiological growth stages, including 10-leaf (S₁), 16-leaf (S₂), tasseling (S₃), milk (S₄) and silage harvest (S₅) (Ritchie *et al.*, 1993). These stages occurred at 25, 46, 63, 91, and 106 DAP in 2009 and at 26, 44, 68, and 97 DAP in 2010 respectively. Total aboveground biomass (TB) was measured four times in 2009 and 2010 (S₁ to S₄), while leaf area (LA) was measured five times (S₁ to S₅) in 2009 and four times (S₁ to S₄) in 2010. At each sampling time, LA was measured via a leaf area meter (Mk2, Delta-T Devices Ltd, Cambridge, UK). To determine TB, the plant samples containing the leaves, stems and ears were oven-dried at a temperature of 75 °C for 48 hours (Torquebiau and Kwesiga, 1996). Leaf area index (LAI) was calculated for each pot from LA measurements.

2.5.2. Root development

Root samples were taken at every growth stage, concurrently with the aboveground measurements to determine root biomass (RB), root biomass density (RBD), and root:shoot ratio (RSR) (Bohm, 1979). After removal of the aboveground components, each pot

wassaturated with water and the root system (excluding aerial [brace] roots) was removed from the soil and washed using a water jet with alow pressure (Pirnajmedin *et al.*, 2015).The washed roots were then oven-dried at 65°C for 48 hours.

2.6. Calculation of K_y and IWUE

The yield response factor (K_y , unitless) was calculated as (Doorenbos and Kassam, 1979):

$$\left(1 - \frac{Y_{ac}}{Y_m}\right) = K_y \left(1 - \frac{ET_{ac}}{ET_m}\right) \quad (10)$$

where, Y (kg ha^{-1}) is yield and ET is crop evapotranspiration (mm) during the measurement period. The subscripts ‘ ac ’ refer to actual for all four irrigation treatments, and ‘ m ’ refer to maximum, for full irrigation treatment (without water stress. In this study, Y was replaced by TB, LA, or RB to estimate $K_{y\text{-TB}}$, $K_{y\text{-LA}}$, and $K_{y\text{-RB}}$ as an indicator of the sensitivity of these variables to water stress under M_1 and M_2 treatments.

Irrigation water use efficiency (IWUE, kg m^{-3}) was calculated as (Howell *et al.*, 1997):

$$IWUE = \frac{Y}{T_{WA}} \quad (11)$$

where, Y is the total aboveground biomass at the silage harvest stage (kg ha^{-1}), and T_{WA} is the total applied water (irrigation + precipitation) up to the growth stage under consideration ($\text{m}^3 \text{ha}^{-1}$).

2.7. Calculation of growing degree days (GDD)

Some of the analysis of maize growth and development was conducted as a function of growing degree days (GDD), °C (Figure 2), which was calculated as follows:

$$GDD = \sum_{i=1}^m \left[\left(\frac{T_{\max} + T_{\min}}{2} \right)_i - T_b \right] \quad (12)$$

where $T_{\min}$ is the daily minimum air temperature at day i ($^{\circ}\text{C}$), $T_{\max}$ is the daily maximum air temperature at day i ($^{\circ}\text{C}$), T_b is the base temperature ($^{\circ}\text{C}$) assumed as 10°C for maize (Kiniry, 1991), and n is the number of days.

2.8. Statistical analysis

We used the General Linear Model to assess the Analysis of variance (SAS Institute, 2001) in statistical software (ver. 9.1 SAS Inst. Cary, NC), and means separation for each of the measured variables. Significant differences among treatments were determined using the Duncan's multiple range test at the 0.05 probability level. Also, data for each deficit-irrigation management strategy (M_1 and M_2) were analyzed separately according to a split plot design.

3. Results and Discussion

Because the S_1 stage was close to the starting date of irrigation treatments, they have little interpretive power, so the statistics for this growth stage are not shown or discussed. However, the values of different variables for this stage are included in the figures to demonstrate the trend during the growing season.

3.1. Maize evapotranspiration, and applied irrigation water

The seasonal grass-reference evapotranspiration (ET_o) for full irrigation (I_4) was 1035 and 1037 mm in 2009 and 2010, respectively, while the calculated maize evapotranspiration under field conditions (ET_{CF}) was 568 and 580 mm for the two years. However, the actual crop evapotranspiration (ET_{CP}) for I_4 derived from the tensiometer measurements was 791 and 839 mm in 2009 and 2010, respectively. The calculated microclimate coefficient (K_{MC}) increased with DAP (Figure 3).

The mean volume of water applied in the two years ($\mu \pm 1$ SE) to the I_1 , I_2 , I_3 and I_4 irrigation levels was 83 ± 3 , 99 ± 3 , 115 ± 4 , and 130 ± 5 liters per plant ($L\ p^{-1}$) for M_1 and 83 ± 0 , 92 ± 5 , 99 ± 6 , and 126 ± 8 $L\ p^{-1}$ for M_2 (Figure 2). Even though, the amount of applied irrigation water was ~6% more for M_1 treatment compared to M_2 , this resulted in no

statistical significance in the amount of irrigation water applied within irrigation levels among years (Table 1).

3.2. Response Variables

There was no significant difference found among replicates among years, and among response variables (Table 1). The main effects of irrigation level (I) were significant across all response variables, i.e. TB, LA, RB, and RSR; and the main effects of DIM strategy (M) were significant for total aboveground biomass and leaf area for both years (Table 1). More specifically;

3.2.1. Total aboveground biomass (TB).

There were interaction effects, where $M \times S$ and $S \times I$ were both significant on TB ($p < 0.01$) for both years, and $M \times I$ and $M \times S \times I$ were only significant in 2009 ($p < 0.01$) (Table 1). Moreover, the effect of irrigation at growth stages S_2 to S_4 on TB was significant for both M_1 ($P < 0.05$) and M_2 ($P < 0.01$) (Table not presented). The mean TB for M_1 and M_2 during the two years was 26.8 and 24.5 t ha⁻¹ for full-irrigation level (I_4) measured at the milk stage. These values were close to those reported by other researchers for non-stressed maize in similar environmental conditions, e.g., Çakir (2004), 23-30 t ha⁻¹, Farré and Faci (2009), 22.73-23.97 t ha⁻¹, Gheysari *et al.* (2009a), 19.90 t ha⁻¹.

Under both M_1 and M_2 strategies, the decrease in the TB was minimal during the vegetative stage but was enhanced (for each irrigation level) as the crop approached the end of the growing season (Table 2). Jama and Ottman (1993) studied the effect of water stress during early growth stages, including anthesis, and found that delay in the first irrigation reduced dry matter accumulation rate at all growth stages up to the milk stage. Short-term water stress at the beginning of rapid vegetative growth stage has been shown to negatively affect dry matter production (NeSmith and Ritchie, 1992; Salvador and Pearce, 1995), and can be explained by a combination of less plant extension growth, delayed leaf tip emergence

and smaller leaf size (Cakir, 2004). In our study, irrigation was applied more consistently and regularly in M_1 compared to M_2 and this has likely ameliorated these adverse effects during the vegetative stage in the fixed irrigation interval strategy. A more timely irrigation strategy (*i.e.*, M_1) has also resulted in less crop stress with M_1 (compared to M_2) during reproductive stages. As a consequence, the TB production was on average was ~25% higher for M_1 compared to M_2 , even though irrigation was only ~6% higher for M_1 .

3.2.2. Leaf area (LA) and leaf area index (LAI)

I, S, and $I \times S$ at all growth stages significantly affected LA ($P < 0.01$) for both years (Table 1). For M_1 , there was significant difference between I_3 and I_4 at S_3 , S_4 and S_5 in 2009 (Table 2). While, for M_2 , the difference in LA between all irrigation levels at all growth stages was significant during both years (Table 2). Except for the full irrigation treatments (*i.e.*, I_4), the LA was generally higher in M_1 compared to M_2 (Figure 4). This partially explains the higher TB production under the M_1 strategy. Larger crop-level leaf surface, produced under M_1 , is likely responsible for increased the transpiration, and consequently larger carbon uptake and biomass allocation.

As expected, LAI increased during the growing season from S_1 to S_3 stage for M_1 and M_2 in both years (Figure 5). Maximum LAI occurred from the tasseling stage to the milk stage under both M_1 and M_2 . The observed reduction in LA agreed with the results from previous studies (McCullough *et al.*, 1994; Kang *et al.*, 1998; Stone *et al.*, 2000; Lizaso *et al.*, 2001). As a remarkable result, however, we found that the rate of change (slope) of this reduction is more intense under the M_2 strategy (Figure 4). From a practical point of view, this means that LA is reduced more severely when increasing the irrigation intervals (M_2) rather than the decreasing irrigation depths (M_1).

LAI also tended to decrease as irrigation application decreased (Figure 5), consistent with results of previous studies (NeSmith and Ritchie, 1992; Bouazzama *et al.*, 2012). The

range of LAI values obtained in this study agrees with those reported for arid and semi-arid conditions by Gheysari *et al.* (2009a) [2.99-4.27] and Bouazzama *et al.* (2012) [3.4-5.1]. In addition, the peak values of LAI under favorable moisture conditions (*i.e.*, I₄ irrigation level), are close to those measured and estimated using the CERES-LA model by Lizaso *et al.* (2003). According to the previous studies, LAI was found to be affected by plant population and hybrid (Baron *et al.*, 2006), weather conditions (Cox, 1996), and planting date (Gheysari *et al.*, 2009a). Results of this study suggest that type of DIM can also affect the LAI of maize.

3.2.3. Root biomass (RB) and root biomass density (RBD)

There was a highly significant effect of I, and S on RB for two years ($P < 0.01$). Furthermore, the effect of irrigation at all growth stages on RB was significant under M₂ ($P < 0.01$) and under M₁ ($P < 0.05$), except at S₂ in 2010 (Table not presented). There was significant difference ($P < 0.05$) in RB between all irrigation levels at different growth stages for M₂ in 2009 and 2010 (Table not presented).

RB increased from S₁ to S₄ and then decreased afterwards for all irrigation levels (Table 2). RB was affected by irrigation level only after S₂ (44-46 DAP). Maximum RB values during both years were obtained at the I₄ irrigation level at the S₄ stage in both DIM strategies (Figure 4). The mean of maximum RB values was 32.54 g m⁻² for M₁ and 34.58 g m⁻² for M₂. As irrigation decreased and the level of crop water stress intensified, RB decreased continuously from I₄ to I₁ in M₁ (Figure 4). The most severe water stress condition (I₁) led to the minimum RB value under both strategies (Figure 4). Studying the effects of DI on Maize, Jama and Ottman (1993) and Kang *et al.* (2000) all came to the same conclusion. A similar tendency was observed for M₂, (with the exception of the I₂ irrigation level), which had overall higher RB production than M₁ (Figure 4). It seems that longer irrigation intervals applied in I₂, compared to I₃, in M₂ altered crop allocation to more RB production. This

conclusion can be further verified with the added result that TB production was less in I₂ compared to I₃.

The mean root biomass density (RBD) during the two years was ($\mu \pm 1$ SE) 215.89 $\pm$ 8, 270.47 $\pm$ 6, 281.88 $\pm$ 30, and 292.19 $\pm$ 15 g m⁻³ soil for the I₁, I₂, I₃, and I₄ irrigation levels, respectively for M₁, and 158.49 $\pm$ 19, 245.38 $\pm$ 20, 206.76 $\pm$ 15, and 302.98 $\pm$ 36 g m⁻³ soil for M₂ (Figure 6).

3.2.4. Root:shoot ratio (RSR)

There was significant effect ($P < 0.01$) of I, S on RSR during both years (Table 1). In addition, there was significant effect of irrigation at all growth stages on RSR in M₁ ($P < 0.05$) during both years (Table not presented). For M₁ and M₂ there was significant difference in RSR between most of the irrigation levels at all growth stages (Table 2). At the S₄ stage, the mean of RSR trend among treatments was the same for the two years, but with an approximate 0.08/0.03 offset—with higher RSR values in 2009 in M₁/M₂. A higher RSR occurred for M₂ compared to M₁ at the S₄ stage during both years (Table 2).

Average RSR (across the two years) during growth stages S₂, S₃ and S₄ varied from 0.09 to 0.25 for M₁ and from 0.12 to 0.27 for M₂ for all irrigation levels. The average RSR (during growth stages) increased from severe to moderate level of DI (I₁ to I₂), decreasing afterwards for I₃ and I₄ as irrigation increased (Table 2). Other researchers have reported increase in RSR due to DI (Kang *et al.*, 1998; Bonifas *et al.*, 2005). Our data specifically shows that RSR was more affected by changing irrigation depth (M₂) compared to the changing irrigation interval (M₁) (Table 2). This further implies that water holding capacity in our system, whether it is in the soil, plants, or both, from increased irrigation depth is more important than the ability of the system to retain water to meet evaporative demand over longer time periods.

3.3. Irrigation water use efficiency (IWUE)

The effect of different irrigation levels on IWUE was significant at S_2 , S_3 , and S_4 ($P < 0.05$). Although there was significant difference between irrigation levels under both DIM's, a clear trend was not found (Table 3). Moreover, in both DIM strategies, IWUE was affected by growth stage and irrigation levels so that from S_2 to S_4 , IWUE increased for all irrigation levels. Average IWUE values for I_4 , during the two years, under M_1 were 1.54, 2.89, and 3.53 kg m^{-3} for S_2 , S_3 , and S_4 , respectively. The corresponding values under M_2 were 1.74, 2.39 and 3.25 kg m^{-3} .

The reported IWUE values here are in the range reported by Djaman and Irmak (2012) [2.97 to 4.87 kg m^{-3}], and Zhang *et al.* (2004) [3.44 kg m^{-3}]. There were interactions among IWUE and growth stage and irrigation levels, such that from S_2 to S_4 , IWUE increased for all irrigation levels. For both strategies, the average IWUE values for I_4 (during the two years) was different across different stages (S_2 , S_3 , and S_4). Sources for this variability may include; changes in weather conditions resulting in a decrease in soil surface evaporation (Djaman and Irmak, 2012), increase in leaf area (vegetation canopy) root development, and better utilization of water and nutrition from the soil profile as the season progressed (Shahnazari *et al.*, 2007). In general, we concluded that on average M_1 had higher IWUE compared to M_2 .

3.4. Response factor to water stress

The response factor to water stress (K_y) for TB (K_{y-TB}), LA (K_{y-LA}) and RB (K_{y-RB}) were calculated combining the results of 2009 and 2010 measured at the milk stage (S_4) under M_1 and M_2 . For example, K_{y-TB} represents the slope of the line between relative reduction in TB (calculated as $1 - TB_{II}/TB_{I4}$) to relative reduction in applied water (calculated as $1 - W_{II}/W_{I4}$). K_{y-TB} was 1.09 for M_1 and 1.62 for M_2 (Figure 7a), indicating that TB of maize plants were 1.5 times more sensitive to water stress under M_2 compared to M_1 . Pearson's correlation

coefficient (r) between relative reduction in TB and relative reduction in applied water was significant at 1% level for both irrigation managements.

K_{y-LA} was 0.30 for M_1 and 0.66 for M_2 (Figure 7b), indicating that LA was approximately twice as sensitive to reduction in irrigation under M_2 compared to M_1 . The r value between relative reduction in LA and relative reduction in applied water was 0.89 for M_1 ($P < 0.01$) and 0.81 for M_2 ($P < 0.05$).

K_{y-RB} was 0.71 for M_1 and 1.15 for M_2 (Figure 7c), meaning that RB was considerably more sensitive to reduction in irrigation under M_2 compared to M_1 . The correlation coefficient (r) of the relationship between relative reduction in RB and relative reduction in applied water was 0.74 for M_1 and 0.87 for M_2 . The slope of the line was statistically significant at the 1% and 5% levels for M_1 and M_2 , respectively. Higher K_y values were found under the M_2 treatment, indicate that TB, LA, and RB are all more sensitive to reduction in water application using the variable irrigation interval-fixed irrigation depth (M_2) strategy compared to the fixed irrigation interval-variable irrigation depth (M_1) strategy. These results are consistent with Fereres and Soriano (2007) and Farré and Faci (2009) who also reported that the type of DIM may affect the conservation of water in maize.

The K_{y-TB} values obtained in this experiment (1.09 for M_1 and 1.62 for M_2) were within the same range as those reported by Payero *et al.* (2009) [1.50] and Bouazzama *et al.* (2012) [1.12] for silage maize in arid and semi-arid areas at different irrigation frequencies. Higher K_y values were found under the M_2 treatment at the Milk stage (S4), indicating that TB, LA, and RB were all more sensitive to reduction in water application using the variable irrigation interval-fixed irrigation depth (M_2) strategy compared to the fixed irrigation interval-variable irrigation depth (M_1) strategy (Figure 7). It should however be noted that there is a large range in K_y values reported in the literature. We interpret our result and those reported elsewhere as the source of variance range in K_y values is due to differences in environmental conditions

e.g., climate and soil conditions (Vaux and Pruitt, 1983; Payero *et al.*, 2008), crop hybrid (Stan and Naescu, 1997), precipitation distribution (Pejić *et al.*, 2012), and crop characteristics (Payero *et al.*, 2008). In this study, we also showed that the type of DIM also affects K_y values for maize.

3.5. Optimal DIM strategy

When we compare M_1 with M_2 , M_1 was more favorable development of maize roots, and also improved IWUE. TB response to water stress and leaf area index (K_{y-TB} and K_{y-LA}) was lower in both M_1 compared to M_2 . Omission of key irrigation events in M_2 had negative effects on productivity, particularly those during the crop development and mid-season stage of maize growth. It is generally known that a lower MAD results in improved IWUE. Hence to better elucidate this idea, MAD in this study was ~ 50% for M_1 whereas it was higher (less irrigation water) under M_2 . Taking these results in concept, M_1 should be considered as an irrigation strategy that would have optimal yield and less risk to productivity than use of M_2 in arid and semi-arid regions. Given that the location of this study and that the variance in results were predominately environmental, we acknowledge increased assurance in yield and reduced risk would be achieved under similar environmental conditions, *i.e.*, Iran. With the goal to reduce risk and optimize yield, our recommendation also includes the use of irrigation systems that provide proven consistent, effective, and high distribution uniformity across a range of irrigation depths (Sadeghi *et al.*, 2015, Kiani *et al.*, 2016), *e.g.*, drip-tape irrigation systems.

It is important to note that (other) irrigation systems substantially differ in their ability of generating wetting patterns, irrigation frequency, spatial uniformity, spatially and temporally consistent gross depth of applied water and their ability to effectively meet a MAD strategy. The interaction among these parameters by a less than optimal irrigation systems and attempting to apply DIM strategies would likely result in different rooting

architecture and functions, and productivity than those found here. That said, we also recognize that our experiments were conducted in pots, with all the associated caveats of pot-conducted research. But because we placed special attention to being able to irrigate with consistent uniformity (*i.e.*, drip-tape system) and reduced bias due to any non-representative microclimate, we interpret our results as a trend analyses. That is, not as absolute, but the expected difference between M_1 and M_2 is a real relative difference, and one would expect to reproduce this difference if they apply this approach under their own site specific environmental and management conditions.

3.6. Crop Physiology

Many of the metrics used here are tools for management (*e.g.*, IWUE, LA, RB, RBD: RSR, TB, etc.), but they also, either directly or indirectly, have a physiological meaning that we often overlook. Plants under stress, in this case maize induced water stress, allocate resources to different functions to optimize their ability to acquire carbon (productivity) and reproduce (develop grain). Their ability to alter their allocation patterns is the degree by which they are genetically pre-disposed to be plastic. When we consider stressing a whole crop to optimize our resource (water) to achieve new productivity and yield goals that can benefit society, we also have the opportunity to optimize the plant's/crop's plasticity in response. This too is often overlooked.

As a thought experiment, the plant's initial plastic responses to water stress and still have ability to acquire carbon and growth (*i.e.*, drought tolerance)--would be to allocate more resources to roots for the acquisition of water and nutrients (Ottman *et al.*, 1996; Fereres and Soriano, 2007), and then create the leaf area and the leaf function that can support what the roots can deliver. We did specifically address these ideas in this study, but results here may provide additional insight in how best optimize future DI strategies.

Wasson et al. (2012), identified four root traits that can improve productivity where stored soil moisture is available (i) deeper root systems, (ii) increased root density at depth, (iii) decreased root density at the surface, and (iv) increased conductance to the movement of water from soil to roots through an increase in root hairs and/or xylem diameters. An increase in the rooting depth (and consequently root biomass) is directly linked to changes in leaf characteristics that optimize transpiration rates, shoot dry weight, stomatal conductance (Kang and Zhang, 2004) and relative water content while still accruing carbon, *i.e.*, measures of WUE and IWUE. In this case, the root biomass can provide useful insight on the crop's plastic ability to manage its water status (Hund et al., 2009). In support of this notion, we observed more rapid increases in root biomass and leaf area in M_1 over M_2 across all growth stages from I_{1-3} , and converged for I_4 where net irrigation depth = $1.0 \times \text{SWD}$ (Eq. 5, Figure 6, and 7, respectively). Breeding trials that can further enhance this plasticity in response, and create less sensitivity to simulated drought in the growth stages of rapid elongation and grain filling stages would advance its successful application of DIM strategies and better meet societal needs of food security in arid and semi-arid environments.

5. Conclusions

This study was conducted to evaluate the effect of two common DIM strategies in an arid region, which included, (i) decreased the amount of applied water compared with crop water needs for each irrigation event (reduction in applied water- M_1), and 2) omission of one or more irrigation events during the growing season (increase in irrigation interval- M_2). In general, there was significant effect of irrigation and growth stage on total biomass, leaf area, root biomass and root-shoot ratio for both DIM strategies during 2009 and 2010. M_1 was found to be a better DIM strategy compared to M_2 because it had more favorable effects on improving the IWUE, total biomass and also maize roots development over the growing season. Other conclusions were as follows:

(i) *Leaf Area (LA) and Leaf Area Index (LAI)*: LAI was significantly reduced by water deficit, with the maximum LAI occurring from the tasseling to the milk stage under the two DIMs. The LA was reduced more severely when increasing the irrigation intervals (M_2) rather than the decreasing irrigation depths (M_1). Results of this study suggest that besides other known factors, the type of DIM can also affect leaf characteristics of maize.

(ii) *Root Biomass (RB) and Root Biomass Density (RBD)*: During both seasons, maximum RB and RBD were observed at the milk stage for both M_1 and M_2 . RB increased from growth stage to milk stage and then decreased afterwards for all irrigation levels. RB was affected by irrigation level only after the leaf stage.

(iii) Under both DIM strategies, the average RSR increased from severe level to moderate level of DI. Afterwards, by increasing irrigation water depth, RSR decreased. In addition, a higher RSR occurred for M_2 compared to M_1 at the S_4 stage during both years. The comparison between the results of RSR in two DIMs indicated that root:shoot ratio was more affected by changing irrigation depth (M_2) compared to the changing irrigation interval (M_1).

(iv) *Irrigation Water Use Efficiency (IWUE)*: Although there was significant difference between irrigation levels under both DIMs, a clear trend was not found. In general, M_1 had higher IWUE compared with M_2 .

(v) *Response factor to water stress (K_y)*: Type of DIM affected the K_y values for maize. The higher K_y values obtained under M_2 indicate that TB, LA, and RB, are all more sensitive to reduction in water application using M_2 strategy compared to M_1 strategy.

6. Acknowledgements

Funding for this study was provided by Iran National Science Foundation (INSF) (project No. 88000841) and Isfahan University of Technology. We also wish to thank Profs. F.

Lamm, S.F.Mousavi, S.M. Mirlatifiand A. Liaghatfor their helpful comments.We gratefully acknowledge the support from Mr. Banifateme,Mr. Rezaee and Ms. Meydanshahi for their invaluable assistance in the field experiments.Authors also respectfully thank the anonymous reviewers for their thoughtful comments.HWL acknowledges the National Science Foundation (NSF) for ongoing support.The NEON is a project sponsored by the NSF and managed under cooperative support agreement (1029808) by NEON, Inc.Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of our sponsoring agencies.This commentary would not have taken shape if it were not for meaningful engagement with community members.

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Table 1. Results of the analysis of variation (ANOVA) for the response variables: Total Aboveground Biomass (TB), Leaf Area (LA), Root Biomass (RB) and Root:Shoot Ratio (RSR) for maize under 2009 and 2010, as a function of potential sources of variation (SV) and their interactive effects. SV included; Replicates (R), Deficit irrigation management strategy (M), Crop growth stage (S), and Irrigation treatment (I).

SV	TB (g p ⁻¹)				LA (cm ² p ⁻¹)				RB (g p ⁻¹)				RSR			
	2009		2010		2009		2010		2009		2010		2009		2010	
	df	M.S. ×10 ³	df	M.S. ×10 ³	df	M.S. ×10 ⁹	df	M.S. ×10 ⁹	df	M.S.	df	M.S.	df	M.S.	df	M.S.
R	2	0.26 ^{ns}	2	0.48 ^{ns}	2	1.44 ^{ns}	2	1.44 ^{ns}	2	3.73 ^{ns}	2	8.58 ^{ns}	2	0.0015 ^{ns}	2	0.0012 ^{ns}
M	1	17.39 [*]	1	54.37 [*]	1	16.52 [*]	1	16.52 [*]	1	305.30 ^{**}	1	74.25 ^{ns}	1	0.0159 ^{ns}	1	0.0155 [*]
S	3	215.11 ^{**}	3	544.54 ^{**}	3	404.10 ^{**}	3	404.10 ^{**}	4	2211.68 ^{**}	3	1701.24 ^{**}	3	0.5507 ^{**}	3	0.2638 ^{**}
M×S	3	8.35 ^{**}	3	18.57 ^{**}	3	3.02 [*]	3	3.02 [*]	4	54.33 ^{**}	3	4.71 ^{ns}	3	0.0045 ^{ns}	3	0.0022 ^{ns}
I	3	16.47 ^{**}	3	47.54 ^{**}	3	48.39 ^{**}	3	48.39 ^{**}	3	218.41 ^{**}	3	247.28 ^{**}	3	0.0298 ^{**}	3	0.0198 ^{**}
M×I	3	4.71 ^{**}	3	0.30 ^{ns}	3	5.84 ^{**}	3	5.84 ^{**}	3	59.98 ^{**}	3	57.12 ^{**}	3	0.0012 ^{ns}	3	0.0120 ^{**}
S×I	9	4.77 ^{**}	9	10.77 ^{**}	9	1.87 ^{**}	9	1.87 ^{**}	12	22.54 ^{**}	9	14.02 ^{ns}	9	0.0033 ^{ns}	9	0.0065 ^{**}
M×S×I	9	2.72 ^{**}	9	1.15 ^{ns}	9	1.26 ^{ns}	9	1.26 ^{ns}	12	7.55 ^{**}	9	4.72 ^{ns}	9	0.0116 ^{**}	9	0.0054 ^{**}

Note: df: degree of freedom; M.S.: mean square; *significant at the p < 0.05 level, **significant at the p < 0.01 level, ns: not significant at p < 0.05 level

Table 2. Total biomass (TB), leaf area (LA), root biomass (RB) and root to shoot ratio (RSR) of maize in different irrigation levels under M₁ and M₂ in 2009 and 2010.

Stage	Treatment		2009				2010			
	Management	Irrigation level	TB	LA	RB	RSR	TB	LA	RB	RSR
			(g p ⁻¹)	(cm ² p ⁻¹)	(g p ⁻¹)		(g p ⁻¹)	(cm ² p ⁻¹)	(g p ⁻¹)	
S2	M ₁	I ₁	26.08 ^{cd§}	2849 ^e	8.90 ^f	0.35 ^b	57.70 ^{bc}	4154 ^e	13.14 ^c	0.23 ^{de}
		I ₂	38.04 ^{bc}	3479 ^c	10.62 ^c	0.28 ^e	69.07 ^b	4700 ^c	15.26 ^b	0.22 ^d
		I ₃	37.92 ^{bc}	3650 ^{cb}	10.34 ^c	0.28 ^e	75.39 ^{ab}	5011 ^b	18.42 ^a	0.24 ^c
		I ₄	47.37 ^{ab}	4353 ^a	10.20 ^c	0.22 ^f	93.56 ^a	4973 ^b	17.56 ^a	0.19 ^e
	M ₂	I ₁	26.08 ^d	2694 ^e	8.09 ^e	0.31 ^c	39.27 ^e	3678 ^g	7.84 ^e	0.20 ^e
		I ₂	29.30 ^c	3189 ^d	11.05 ^b	0.38 ^a	48.21 ^d	4085 ^f	14.54 ^c	0.30 ^a
		I ₃	35.20 ^{bc}	3802 ^b	9.46 ^d	0.27 ^c	52.86 ^c	4508 ^d	11.31 ^d	0.21 ^e
		I ₄	52.36 ^a	4752 ^a	12.07 ^a	0.23 ^f	71.97 ^b	5163 ^a	18.44 ^a	0.26 ^b
S3	M ₁	I ₁	91.63 ^d	4712 ^d	16.48 ^d	0.18 ^{ab}	215.48	5711 ^b	17.48 ^d	0.09 ^d
		I ₂	123.25 ^b	4801 ^d	23.31 ^a	0.19 ^a	219.72 ^d	5459 ^c	24.76 ^{ab}	0.13 ^c
		I ₃	151.69 ^a	5776 ^a	22.73 ^{ab}	0.15 ^c	352.17 ^b	6062 ^a	26.26 ^{ab}	0.08 ^{de}
		I ₄	146.73 ^{ab}	4881 ^d	25.32 ^a	0.17 ^b	404.66 ^a	6058 ^a	28.15 ^a	0.07 ^e
	M ₂	I ₁	64.97 ^f	3850 ^e	11.82 ^e	0.18 ^{ab}	100.68 ^g	4658 ^e	15.88 ^d	0.16 ^b
		I ₂	89.88 ^e	4729 ^d	18.37 ^c	0.20 ^a	125.02 ^f	5026 ^d	23.37 ^b	0.19 ^a
		I ₃	111.43 ^c	5298 ^c	15.42 ^d	0.14 ^d	172.59 ^e	5372 ^c	20.03 ^c	0.12 ^c
		I ₄	151.29 ^a	5911 ^b	21.56 ^b	0.14 ^d	254.26 ^c	5862 ^b	28.90 ^a	0.11 ^{cd}
S4	M ₁	I ₁	217.50 ^d	3852 ^f	25.46 ^c	0.12 ^c	324.35 ^d	5665 ^b	23.23 ^d	0.07 ^c
		I ₂	269.33 ^c	3951 ^f	29.17 ^{bc}	0.11 ^c	352.16 ^d	5644 ^b	30.29 ^{bc}	0.09 ^a
		I ₃	276.77 ^c	4112 ^e	29.95 ^b	0.11 ^c	428.82 ^c	5905 ^b	32.86 ^b	0.08 ^b
		I ₄	342.48 ^a	4361 ^d	32.22 ^a	0.09 ^d	513.66 ^a	6117 ^{ab}	31.70 ^b	0.06 ^c
	M ₂	I ₁	85.45 ^g	4494 ^d	16.62 ^c	0.19 ^b	222.00 ^f	5006 ^c	20.24 ^e	0.09 ^a
		I ₂	107.13 ^f	5043 ^c	26.37 ^c	0.25 ^a	299.93 ^e	5433 ^b	28.54 ^c	0.10 ^a
		I ₃	206.66 ^e	5921 ^b	22.80 ^d	0.11 ^c	413.66 ^c	5995 ^b	24.23 ^d	0.06 ^c
		I ₄	318.92 ^b	6497 ^a	32.41 ^a	0.10 ^{cd}	465.08 ^b	6533 ^a	36.75 ^a	0.08 ^b
S5	M ₁	I ₁		2873 ^d	24.69 ^b					
		I ₂		3838 ^c	27.73 ^{ab}					
		I ₃		4085 ^b	25.95 ^b					
		I ₄		4199 ^a	28.44 ^a					
	M ₂	I ₁		2663 ^d	13.01 ^d					
		I ₂		3492 ^c	23.06 ^b					
		I ₃		4695 ^b	19.32 ^c					
		I ₄		5431 ^a	28.60 ^a					

Note: I₁ = severe-deficit-irrigation level (0.55SWD for M₁, and MAD= 0.85 for M₂); I₂ = moderate-deficit-irrigation level (0.7SWD for M₁, and MAD=0.75 for M₂); I₃ = mild-deficit-irrigation level (0.85SWD for M₁ and MAD=0.65 for M₂); I₄ = full-irrigation level (1.0SWD for M₁ and MAD= 0.50 for M₂); S₂ =16-leaf stage; S₃ = tasseling stage; S₄ = milk stage; S₅ = silage harvest stage. § No significant difference at 0.05 probability level (according to Duncan's Multiple Range Test) is noted by at least one common letter when irrigation level (I) and management strategy (M) were compared at each stage. Values are average of three replications.

Table 3. Irrigation water use efficiency (IWUE) of maize under different irrigation levels for M₁ and M₂ in 2009 and 2010. Values are $\mu \pm \text{SE}$.

Maize growth stage	Irrigation levels	2009		2010	
		M ₁	M ₂	M ₁	M ₂
		IWUE (kg m ⁻³)			
S ₂	I ₁	0.63 $\pm$ 0.11 ^{c§}	0.67 $\pm$ 0.01 ^b	1.47 $\pm$ 0.19 ^c	0.99 $\pm$ 0.03 ^b
	I ₂	0.83 $\pm$ 0.09 ^a	0.75 $\pm$ 0.03 ^b	1.97 $\pm$ 0.38 ^a	1.04 $\pm$ 0.04 ^b
	I ₃	0.75 $\pm$ 0.20 ^b	0.78 $\pm$ 0.03 ^b	2.03 $\pm$ 0.35 ^{ab}	1.01 $\pm$ 0.03 ^b
	I ₄	0.87 $\pm$ 0.05 ^a	1.04 $\pm$ 0.01 ^a	2.20 $\pm$ 0.17 ^a	1.22 $\pm$ 0.04 ^a
S ₃	I ₁	1.56 $\pm$ 0.16 ^c	1.14 $\pm$ 0.03 ^d	3.41 $\pm$ 1.15 ^b	1.92 $\pm$ 0.08 ^c
	I ₂	1.82 $\pm$ 0.07 ^a	1.39 $\pm$ 0.04 ^c	3.46 $\pm$ 0.38 ^{ab}	2.13 $\pm$ 0.08 ^c
	I ₃	1.98 $\pm$ 0.34 ^a	1.64 $\pm$ 0.03 ^b	3.89 $\pm$ 0.54 ^a	2.65 $\pm$ 0.08 ^b
	I ₄	1.71 $\pm$ 0.02 ^b	1.87 $\pm$ 0.03 ^a	4.08 $\pm$ 0.24 ^a	2.90 $\pm$ 0.09 ^a
S ₄	I ₁	3.02 $\pm$ 0.37 ^{ab}	1.18 $\pm$ 0.04 ^b	3.92 $\pm$ 0.38 ^a	2.77 $\pm$ 0.11 ^d
	I ₂	3.19 $\pm$ 0.12 ^a	1.34 $\pm$ 0.02 ^b	3.57 $\pm$ 0.13 ^b	3.22 $\pm$ 0.08 ^c
	I ₃	2.85 $\pm$ 0.10 ^b	2.40 $\pm$ 0.08 ^a	3.56 $\pm$ 0.27 ^b	4.15 $\pm$ 0.06 ^a
	I ₄	3.12 $\pm$ 0.08 ^a	2.88 $\pm$ 0.03 ^a	3.94 $\pm$ 0.41 ^a	3.62 $\pm$ 0.05 ^b

Note: I₁ = severe-deficit-irrigation level (0.55SWD for M₁, and MAD= 0.85 for M₂); I₂ = moderate-deficit-irrigation level (0.7SWD for M₁, and MAD=0.75 for M₂); I₃ = mild-deficit-irrigation level (0.85SWD for M₁ and MAD=0.65 for M₂); I₄ = full-irrigation level (1.0SWD for M₁ and MAD= 0.50 for M₂); S₂ =16-leaf stage; S₃ = tasseling stage; S₄ = milk stage. [§] No significant difference at 0.05 probability level (according to Duncan's Multiple Range Test) is noted by at least one common letter when irrigation level (I) were compared at each stage.

Figure Captions:

Figure 1. Minimum ($T_{\min}$) and maximum air temperature ($T_{\max}$), average relative humidity (RH) and daily reference evapotranspiration (ET_0) during the growing season in 2009 and 2010.

Figure 2. Cumulative growing degree days (GDD), cumulative applied water and dates of fertilizer application during the growing season in M_1 and M_2 in 2009 and 2010. M_1 : fixed irrigation interval-variable irrigation depth management [I_1 : 0.55 SWD, I_2 : 0.70 SWD, I_3 : 0.85 SWD, I_4 : 1.0 SWD]; M_2 : variable irrigation interval-fixed irrigation depth management [I_1 : MAD= 0.85, I_2 : MAD=0.75, I_3 : MAD=0.65, I_4 : MAD= 0.50].

Figure 3. Microclimate coefficient (K_{MC}) of maize crop in pot conditions during growth stages.

Figure 4. Trend of total aboveground biomass (TB), leaf area (LA) and root biomass (RB) at different irrigation levels under M_1 and M_2 managements. * The values are average of the data in 2009 and 2010.

Figure 5. Leaf area index (LAI) of maize crop under M_1 and M_2 in 2009 and 2010. M_1 : fixed irrigation interval-variable irrigation depth management [I_1 : 0.55 SWD, I_2 : 0.70 SWD, I_3 : 0.85 SWD, I_4 : 1.0 SWD]; M_2 : variable irrigation interval-fixed irrigation depth management [I_1 : MAD= 0.85, I_2 : MAD=0.75, I_3 : MAD=0.65, I_4 : MAD= 0.50]. * The values are average of three replications.

Figure 6. Root biomass density (RBD) of maize crop under M_1 and M_2 in 2009 and 2010. M_1 : fixed irrigation interval-variable irrigation depth management [I_1 : 0.55 SWD, I_2 : 0.70 SWD, I_3 : 0.85 SWD, I_4 : 1.0 SWD]; M_2 : variable irrigation interval-fixed irrigation depth management [I_1 : MAD= 0.85, I_2 : MAD=0.75, I_3 : MAD=0.65, I_4 : MAD= 0.50]. * The values are average of three replications.

Figure 7. Relative reduction in total aboveground biomass ($1-TB_{Ii}/TB_{I4}$), leaf area ($1-LA_{Ii}/LA_{I4}$) and root biomass ($1-RB_{Ii}/RB_{I4}$) to relative reduction in applied water ($1-W_{Ii}/W_{I4}$) at milk stage under M_1 and M_2 in 2009 and 2010. M_1 : fixed irrigation interval-variable irrigation depth management; M_2 : variable irrigation interval-fixed irrigation depth management; W_{I4} : depth of applied water at full-irrigation level; W_{Ii} : depth of applied water at each irrigation level; LA_{I4} : LA at full-irrigation level; LA_{Ii} : LA at each irrigation level. ** and * indicate that regression line is statistically significant at 1% and 5% levels, respectively.

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

Fig. 5.

Fig. 6.

Figure7

Fig. 7