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Comparison of deficit irrigation management strategies on root, plant growth and biomass productivity of silage maize

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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.

1. 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

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.

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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.*, 0.85–8.64 kg m^{-3} for IWUE and 0.76 to1.5 for K_y, rf. 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 (Dağ̂delen 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 (Kang 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 (rf. Muchow and Davis, 1988; Semere and Froud-Williams, 2001), ii) model productivity based on the intercepted photosynthetically active radiation (IPAR) (rf. 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., 2000; 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 single cross) 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 12.5–46% in 2010 (Fig. 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 plot), which consisted of a total of 120 black polyethylene pots (60 pots for each DIM strategy = 4 irrigation levels × 5 growth stages × 3 replications). Please notice that a total number of 15 pots were available for each deficit irrigation management and each irrigation level (for the whole growing season). This is while our samples were taken only at 5 growing stages. At each growing stage, 3 pots were taken out. so by the end of the season, all the 15 available pots (for a specific DIM strategy and a specific irrigation level) would be taken out.

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 (the saturated paste extract) was 1.9 dS m^{-1} in 2009 and 1.8 dS m^{-1} in 2010. The pH was 7.6 and 7.9 in 2009 and 2010, respectively. Bulk density was 1.28 g cm^{-3} in 2009 and 1.41 g cm^{-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 × 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 out-