Agricultural Water Management 140 (2014) 69–78

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Optimal coupling combinations between the irrigation rate and glycinebetaine levels for improving yield and water use efficiency of drip-irrigated maize grown under arid conditions

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ARTICLE INFO

Article history:
Received 9 October 2013
Received in revised form 17 March 2014
Accepted 30 March 2014
Available online 19 April 2014

Keywords:
Deficit irrigation
Drip irrigation
Relative water content
Seasonal yield response factors
Threshold level
Water potential

ABSTRACT

This study was conducted over 2 years (2011 and 2012) to determine the optimal combinations between the irrigation rate and glycinebetaine (GB) levels in order to maximise yield and irrigation water use efficiency (IWUE) for drip-irrigated maize. A field experiment was performed using a randomised complete block split plot design with three drip irrigation rates (I_1: 1.00, I_2: 0.80, and I_3: 0.60 of the estimated evapotranspiration, ET) and five GB levels (GB_0, GB_{25}, GB_{50}, GB_{75} and GB_{100}, GB levels at 0, 25, 50, 75 and 100 mM, respectively) as the main and split plots, respectively. We found that although exogenously applied GB appeared to have different effects on yield variables and IWUE, these differences were dependent on the level of GB within the same irrigation rate. The grain yield and yield component values for I_2GB_{50} treatment were occasionally comparable to those obtained for I_1GB_0 treatment, and the values for both treatments were higher than those obtained for I_1GB_{75} or I_1GB_{100}. I_3GB_{50} or I_3GB_{100} had grain yield and yield component values similar to those obtained for I_2GB_0 and I_2GB_{100}. The highest value for IWUE was found for I_2GB_{50} and this value was similar to that obtained with I_3GB_{75}, while the lowest values were obtained for I_1GB_{75} or I_1GB_{100}. Medium GB levels were effective under I_2 and I_3 treatments to obtain the lowest value for seasonal yield response factors (k_y). The production functions of yield versus GB levels were second-order relationship for all drip irrigation rates. In conclusion, exogenous application of GB has the potential to improve yield and IWUE under limited water application, while a threshold level of GB was required for a positive effect.

1. Introduction

Water is a major factor in each of the three pillars of sustainable development; economic, social and environmental, and it plays an important role in daily human activity as well as in poverty avoidance. Because the agriculture sector is the largest single user of fresh water, and accounts for approximately 75% of the freshwater use worldwide, many governments in arid and semi-arid regions issued some regulations to restrict irrigation water use in this sector. Such regulations include the installation of water meters on pumping stations, a moratorium on drilling new wells, and limitations in ground water pumping to fixed multi-year water allocations. These new regulations will decrease the water allocations for each crop because the cost of irrigation water may not be compensated by the increase in yield under well watered conditions. Thus, it is important to apply some targeted agronomic activities to decrease the amount of water used in this sector. Among these activities, applying water below the full crop-water requirement (evapotranspiration) plays a very significant role in reducing irrigation water use in the agriculture sector.

However, maize has been reported to be very sensitive to water deficit particularly during the reproductive stages (tasselling, silking, or grain filling) (NeSmith and Ritchie, 1992). In addition, Rhoades and Bennett (1990) and Lamm et al. (1995) both reported that it is difficult to plan deficit irrigation for maize without an accompanying reduction in the final yield. Thus, the deficit irrigation for furrow-irrigated maize can result in more dramatic fluctuations in grain yield and it will also lessen irrigation water use efficiency (IWUE) due to an increase in the amount of water

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http://dx.doi.org/10.1016/j.agwat.2014.03.021
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that moves beneath the root zone. Because drip irrigation is capable of applying small amounts of water precisely where it is needed and with a high degree of uniformity and frequency, the grain yield and IWUE of drip-irrigated maize could be improved under limited water applications due to the ability of the drip irrigation system to create adequate soil water contents around the emitters. However, several studies have shown that the soil water content that develops around the emitters is strongly related to the water application rate because of its effects on root distribution around the emitter, amount of water uptake by the roots and the amount of water percolation under the root zone (Assouline, 2002; Wang et al., 2006; El-Hendawy et al., 2008a; El-Hendawy and Schmidhalter, 2010). Thus, the water application rates needed to achieve maximum yield and IWUE under limited water applications require the establishment of optimal soil water contents around the emitters without moving the water beyond the active rooting zone or failing to meet the water requirement of the plant.

In addition, maize yields under drip irrigation are generally a linear function of the seasonal ET and yields are usually lower if ET is less than optimal. For example, El-Hendawy et al. (2008b) and El-Hendawy and Schmidhalter (2010) found that the decreases in the grain yield of maize drip irrigated for 0.80 and 0.60 ET compared to 1.00 ET were approximately 18.0 and 60.0%, respectively. This also indicated that applying water below the full crop-water requirement under the drip irrigation system requires further approaches to mitigate the adverse effects of this water deficit. A potential approach to reduce water deficit-induced crop losses is the exogenous application of osmolytes that do not interfere with enzymatic functions (Ashraf and Foolad, 2007; Chen and Murata, 2008). These osmolytes are usually accumulated in the cytoplasm of plant cells to maintain continuous water absorption at low soil water potential (Robinson and Jones, 1986). Glycinebetaine (GB) is an organic compatible solute that accumulates in plants as a defensive response to different stressors (Agboma et al., 1997a,b; Diaz-Zorita et al., 2001; Ashraf, 2009; Chen and Murata, 2008; Hussain et al., 2008, 2009). This compatible solute facilitates the maintenance of water potential equilibrium in the cell, which in turn, maintains turgor pressure during water deficit conditions (Reddy et al., 2013). Interestingly, although maize has a relatively low capacity for GB accumulation, it can absorb and accumulate exogenous foliar application of GB at a significantly high level and translocate it immediately after application to nearly all of the plant parts (Rhodes et al., 1989; Mäkelä et al., 1996; Yang and Lu, 2006). Thus, foliar application may increase the levels of GB in maize genotypes that are unable to synthesise this compound. Most importantly, foliar application of GB may be a simple and cost effective methodology to increase the net benefit under limited water application (Ashraf and Foolad, 2007; Chen and Murata, 2008). Brand et al. (2007) reported that foliar application of GB could be adapted as a management strategy to alleviate water deficit at a cost of less than $25/hectare. Under furrow irrigation application, Hussain et al. (2008) found that foliar application of GB reduced water consumption by 25%, increased cost by only 6% and increased net income by approximately 9% when the sunflower plants were exposed to water stress and treated with exogenous applications of GB at the vegetative and flowering stages. Thus, exogenous applications of GB are an economically feasible approach to counteract the adverse effects of water deficit on maize production.

In light of these facts, the objectives of this study were: (1) to evaluate the impacts of various drip irrigation rates and GB levels on maize production and irrigation water use efficiency (IWUE), and (2) to establish the optimum coupling combinations between the irrigation rate and GB levels in order to achieve maximum yield and IWUE for drip-irrigated maize grown under either sufficient or limited water application.

2. Materials and methods

2.1. Experimental site and conditions

Field experiments of drip-irrigated maize were performed during the 2011 and 2012 growing seasons at the Experimental Farm of the Faculty of Agriculture, Suez Canal University, Ismailia, Egypt (30°58′ N latitude, 32°23′ E longitude and 13 m above sea level). The climate in this region is almost arid. Detailed climatic parameters for Ismailia during the both years are given in Table 1. No rainfall events occurred during the period of experiment from May to September. Prior to the start of the experiment, soil samples were obtained with an auger from soil depths of 0–30 and 30–60 cm to determine the physical and chemical properties of the experimental field (Table 2). The soil texture at this site was predominantly sandy throughout the whole soil profile (75.2% coarse sand, 20.9% fine sand, 2.6% silt and 1.3% clay). The soil bulk density was determined using 100 mm wide and 60 mm high undisturbed soil cores in accordance with the classical method described by Grossmann and Reinsch (2002). The soil water content at field capacity was determined in the laboratory using a pressure plate technique at −0.03 MPa (Klute, 1986).

2.2. Experimental design, treatments and agronomic practices

A randomised complete block split-plot design with three replications was used in each season. Different treatments of water application rates and levels of exogenous application of glycinebetaine (GB) were randomly assigned to the main and split plots, respectively.

The drip irrigation system was divided into three main sectors, where the three irrigation treatments were assigned to the three sectors, with three replications within each sector. Each sector had one flow meter and one pressure valve to control the operating pressure and to measure the irrigation quantity. The three irrigation treatments were I_1: 1.00, I_2: 0.80 and I_3: 0.60 of the estimated crop evapotranspiration (ET), which represented 625.3, 500.2 and 375.2 mm ha^{-1} of water, respectively. The dates of each irrigation event and the quantities of water applied are given in Table 3.

The amount of irrigation water applied, I, was determined from the calculated water requirement for maize (mm) as determined from the crop coefficient (K_c) and the daily reference evapotranspiration (ET_o) using the following equation:

$$I = ET_o \times K_c \tag{1}$$

ET_o was calculated using the Penman–Monteith method (Allen et al., 1998) and the daily data obtained from a meteorological station located within 500 m of the research site. The FAO Penman–Monteith equation, given by Allen et al. (1998):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\left(900/T + 273\right)u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{2}$$

where ET_o is the reference evapotranspiration (mm day^{-1}), Δ represents the slope of the saturation vapour pressure temperature relationship, R_n represents the net radiation at the crop surface (MJ m^{-2} day^{-1}), G represents the soil heat flux density (MJ m^{-2} day^{-1}), γ represents the psychrometric constant, T represents the mean daily air temperature at 2 m height (°C), u_2 represents the wind speed at 2 m height (m s^{-1}), e_s represents the saturation vapour pressure (kPa), e_a represents the actual vapour pressure (kPa), and $e_s - e_a$ is the saturation vapour pressure deficit (kPa).

The K_c is defined as the ratio of the crop evapotranspiration rate to the reference evapotranspiration rate. Because localised K_c values were not available for the study area, the values of K_c suggested