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Supplemental irrigation at tasseling optimizes water and nitrogen distribution for high-yield production in spring maize

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ABSTRACT

The penalty of spring maize yield is often observed due to annual and seasonal fluctuations of precipitation. To achieve a high and stable maize yield, supplemental irrigation is necessary for spring maize. In this study, a 3-year field experiment was conducted during the 2014–2016 growing seasons. A single supplemental irrigation was applied at V6 (I_{V6}), V12 (I_{V12}), tasseling (I_T) and 15 days after silking (I_{S15}), respectively. The water and nitrogen consumption percentages at pre- and post-silking, source-sink relations and yield responses to various irrigation strategies were investigated. The post-silking water consumption percentage with the late irrigation treatments (I_T and I_{S15}) increased by 18.7–40.1% compared with those of I_{V6} and I_{V12}. However, there were no significant differences among the treatments in the nitrogen consumption percentages, and the main variation came from year type. The nitrogen contents in the vegetative parts at silking in I_{V6} and I_{V12} were 10.1–48.9% greater compared to I_T and I_{S15}, i.e., more nitrogen was used before silking compared with I_T and I_{S15}. Supplemental irrigation at tasseling significantly accelerated kernel sink establishment and optimized the relation between source and sink, which improved post-silking biomass production and resulted in high yield and a high harvest index. Regression analysis demonstrated that, to some extent, greater water (20–50%) or nitrogen (40–60%) consumption percentages, higher post-silking biomass production and higher yield could be achieved. Overall, supplemental irrigation at tasseling could optimize water and nitrogen distribution for kernel growth and development and improve the sink capacity to achieve high yield and resource use efficiency.

1. Introduction

The conventional double cropping system of winter wheat and summer maize rotation in the North China Plain (NCP) plays a vital role in supplying grain to China (Li et al., 2005). However, this main system consumes between 800 and 850 mm of water annually, which significantly exceeds the amount of local rainfall (Liu et al., 2002; Sun et al., 2010). Reducing irrigation, especially in winter wheat, is used to increase water use efficiency (WUE) and maintain yield (Li et al., 2005, 2010; Wang et al., 2016). Nevertheless, groundwater overdraft problems are still serious under the optimized irrigation regimes, raising the concerns of both the public and the government (Sun et al., 2015). Spring maize can probably serve as an important cropping pattern due to sufficient temperature and light resources and high WUE and yield potential in the NCP.

However, the annual and seasonal fluctuations of precipitation frequently lead to drought stress in spring maize at each growth stage (http://data.cma.cn/, Fig. 1). Water deficiencies at the different growth stages have diverse effects on maize growth due to sensitivity differences to drought (Cakir, 2004). In general, maize appears to be relatively tolerant to water deficiencies imposed during the vegetative and ripening periods (Claassen and Shaw, 1970; Doorenbos and Kassam, 1979; Hall et al., 1981; Grant et al., 1989), while around flowering, moisture stress results in embryo abortion (Setter et al., 2001; Zinselmeier et al., 1999) and significantly reduces grain yield (Cakir, 2004). To avoid water stress during critical growth stages, supplemental irrigation could be an appropriate choice in order to avoid a high yield penalty and increase WUE when water resources are restricted or the cost is excessive (Iqbal et al., 2014). Igbadun et al. (2007) suggested that good yields could be obtained with regular irrigation at the flowering growth stage, even if irrigation is limited during the vegetative and grain-filling stages. Li and Sun (2016) also showed that an application of a single irrigation can increase maize yield in both black soil and aeolian sandy soil, and supplemental irrigation in late June to early July (around silking) was recommended for maximizing maize yield and WUE in aeolian soil (10.73 Mg ha^{-1} and 27.94 kg ha^{-1} mm^{-1}) and in black soil (11.20 Mg ha^{-1} and 27.70 kg ha^{-1} mm^{-1}) with the lowest yield risk.

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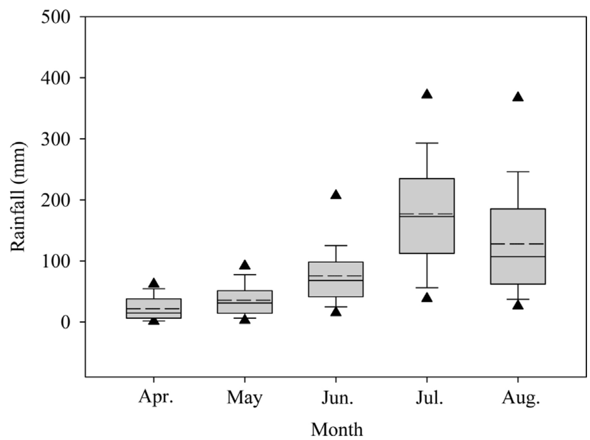

Fig. 1. Average monthly precipitation during spring maize growing seasons in Wuqiao over 1986–2016. The box plots show the 5, 25, 50, 75 and 95 percentiles. The dotted lines and solid lines in the box plots indicate the mean and medium, respectively. The triangles indicate the minimum and maximum.

It is well known that post-silking assimilation contributes approximately 90% to maize yield (Simmons and Jones, 1985; Swank et al., 1982), in consequence, taking necessary steps to guarantee maize production after silking plays an important role in obtaining high grain yield. In addition, water and nitrogen are the most limiting factors for grain yield of maize (Moser et al., 2006), and finite water and nitrogen should be allocated to the filling stage for matter production after silking. Previous studies have examined the effects of irrigation at tasseling on WUE and maize yield (Igbadun et al., 2007; Li and Sun, 2016). However, how supplemental irrigation regulates water and nitrogen temporal distribution and the relations between yield and water/nitrogen consumption percentage at pre- and post-silking are still unclear. In addition, the effects of supplemental irrigation on source-sink changes remains to be further investigated. In this study, we hypothesized that (1) supplemental irrigation at tasseling could increase post-silking water and nitrogen consumption percentages to optimize water and nitrogen temporal distribution and that (2) irrigation at flowering would stimulate kernel sink creation and promote biomass production after silking, resulting in a high harvest index, yield and water and nitrogen use efficiency. We also had the objective to establish a simple and practical irrigation strategy for spring maize production in the NCP.

2. Materials and methods

2.1. Experimental site

The present experiment was conducted in 2014, 2015 and 2016 at Wuqiao Experimental Station of China Agricultural University (Hebei Province, China, 116.3° E, 37.4° N, altitude 20 m). The soil in the field was light loam with 11.8% clay, 78.1% silt and 10.1% sand. In the 2 m soil profile, average bulk density was 1.51 g cm^{-3}, average field capacity was 27.6% (g g^{-1}), and wilting point was 8.6% (g g^{-1}). The upper 40-cm soil profile contained 1.17% total organic matter, 0.95 g kg^{-1} total N, 104.4 mg kg^{-1} available potassium and 29.2 mg kg^{-1} available phosphorus. Soil physical and chemical properties were measured at the beginning of the field experiment.

From 1986 to 2016, during the entire spring maize growing season (April–August), the mean precipitation was 442 mm, with a range of 142–730 mm with a coefficient of variation (CV) of 33.4%. Rainfall was mainly concentrated in July and August (Fig. 1) with a CV of 49.8% and 71.5%, respectively, i.e., rainfall was extremely uneven, and water scarcity could occur at each growth stage of spring maize.

Table 1
The treatments and irrigation regimes used in the present study.

Irrigation	Growth stage	Irrigation date (DAP)	Irrigation water amount (mm)
CK	–	–	–
I_{V6}	V6	41	75
I_{V12}	V12	61	75
I_T	Tasseling	71	75
I_{S15}	15 DAS	87	75

DAP, days after planting; DAS, days after silking.
The data of V6 and 15 DAS in 2015 was 40 DAP and 88 DAP, respectively.

2.2. Experimental design

Zhengdan958, a commonly planted cultivar in China, was manually sown at the density of 72,000 plants ha^{-1} on 22 April 2014, 20 April 2015 and 22 April 2016. Before sowing, 75 mm water was applied to guarantee germination using the surface flood method through plastic pipe. Supplemental irrigation was applied at V6 (I_{V6}), V12 (I_{V12}), tasseling (I_T) and at 15 days after silking (I_{S15}) (Ritchie et al., 1992) at 75 mm (Table 1) with surface flood method through plastic pipe, respectively. A flow metre was used to measure the amount of water supplied. The experimental design was a random complete block design with three replications, and the plot size was 8 m wide by 10 m long with a 2-m buffer zone between plots. In every year, fertilizer containing 72 kg N ha^{-1}, 105 kg P_2O_5 ha^{-1} and 120 kg K_2O ha^{-1} was applied before sowing. Later, 108 kg N ha^{-1} of fertilizer was applied at V12. Pest, disease and weed management followed common practices. The maize was harvested on 7 September 2014, 4 September 2015 and 2 September 2016.

2.3. Sampling and measurements

2.3.1. Soil water content measurements

Soil water content measurements were taken at sowing (VS, seven days after irrigation), silking (R1, before irrigation treatment), and maturity (R6). Soil samples were collected from the 0 to 200 cm soil layer at 20-cm intervals with a soil corer. Soil gravimetric water content (g water g^{-1} dry soil) was measured by oven-drying samples at 105 °C for 48 h to a constant weight. Maize water consumption amount, i.e., evapotranspiration (ET, mm), was calculated using the soil water balance equation (James, 1988) as follows:

$$ET = P + I + \Delta SWS - R - D + CR$$

where P (mm) was the effective rainfall, I (mm) was irrigation, ΔSWS (mm) was apparent change of soil water storage in the 200-cm soil profile between sowing and silking and silking and maturity, R was runoff (considered zero because the experimental plots were surrounded with dikes), D was drainage below the 200 cm soil profile, and CR was capillary rise into the root zone. Because the groundwater table at the experimental site was 7–9 m (> 4 m) below the ground surface, CR and D can be ignored (Wang et al., 2013).

2.3.2. Biomass, leaf area and nitrogen content

At silking and maturity, three representative plants were sampled per plot. A leaf was considered to have senesced when half or more of its area had yellowed. The leaf area (LA) was measured with a ruler to record length (L, from ligule to leaf tip) and width (W, the widest portion of the leaf blade) to calculate according to the formula: LA = 0.75 × W × L. And leaf area index (LAI) = leaf area per plant/land area per plant (Ren et al., 2016). Next, maize was divided into the stem, leaf, grain and bract + cob to be dried at 80 °C for 48 h to a constant weight. The total N content was determined by the Kjeldahl method (Dordas and Sioulas, 2009). Dry matter and N remobilization were calculated as follows according to Cox et al. (1985) and Ruisi et al. (2016):