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Improving water use efficiency and grain yield of winter wheat by optimizing irrigations in the North China Plain

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ABSTRACT

Achieving the combination of high water use efficiency (WUE) and high yield is very important for the sustainable development of wheat production in the North China Plain (NCP). For this study, we investigated how to optimize timing of two irrigations to improve winter wheat grain yield and WUE under field conditions. No-irrigation after sowing (W0) as a control, and six irrigation treatments as follows: irrigation of 75 mm each at late tillering and booting (TB), at late tillering and anthesis (TA); at late tillering and medium milk (TM), at jointing and anthesis (JA), at jointing and medium milk (JM) and at booting and medium milk (BM). Experiments were conducted between the 2014–2016 growing seasons. In all the treatments, JA achieved the highest grain yield (9,267.6 kg ha^{-1}) and WUE (20.2 kg ha^{-1} mm^{-1}). Compared with TB, TA and TM, JA coordinated pre- and post-anthesis water use, reduced pre-anthesis and total evapotranspiration (ET), and increased post-anthesis water use amount and ratio; JA reduced biomass at anthesis, but optimized allocation of assimilation, increased spike partitioning index and maintained high fruiting efficiency, and thus obtained the highest grain number per m^2 (GN, 23.7 10^3 m^{-2}). Meanwhile, JA optimized crop characteristics with appropriate leaf area index (LAI), delayed leaf senescence, extended grain filling duration by 1–3 days, then increased biomass post-anthesis and harvest index (HI). Compared with JM and BM, JA increased GN, biomass post-anthesis and grain yield as well. These results demonstrated that irrigation at jointing and anthesis could improve grain yield and WUE by increasing biomass post-anthesis, HI and GN. Therefore, we propose that under adequate soil moisture conditions before sowing, two irrigations at jointing and anthesis with 150 mm irrigation amount is the optimal limited irrigation practice for wheat production in NCP.

1. Introduction

The North China Plain (NCP) covers 40% of total cultivated area and provides about 61% of the nation's wheat with less than 8% of the total water resources in China (Cai, 2008; Sun et al., 2011). Rainfall cannot match winter wheat water requirements as only 20%–30% of annual precipitation (about 110–180 mm) occurs during the winter wheat growing season (Sun et al., 2011; Fang et al., 2010). Meanwhile, water shortages are becoming increasingly serious (Jiang, 2009). In order to obtain high grain yield, flood irrigation is commonly applied three or four times using more than 300 mm of irrigation water during the growing season (Li et al., 2012; Sun et al., 2011). This irrigation procedure improves grain yield, but reduces WUE due to supplying too much water (Zhang et al., 2017). Over-exploitation of ground-water aggravates water scarcity, reduces the groundwater table and threatens sustainable agriculture (Sun et al., 2006; Kang, 2014). Therefore, deficit irrigation is critical for maintaining high wheat production, and an optimal irrigation water management scheme must be developed for ecological security and sustainable development of winter wheat production in this region.

There are two key strategies to achieve higher WUE. One strategy uses less water to produce the same grain yield (Zhang et al., 2017). Previous studies have resulted in higher WUE with less irrigation or reduced irrigation frequency (Qiu et al., 2008; Nasseri and Fallahi, 2007) without consistent change of grain yield (Man et al., 2015; Xu et al., 2016). The irrigation amount decreased significantly when irrigation frequency was decreased from 4 to 2 times, meanwhile, WUE increased from 0.4 to 2.9 kg mm^{-1} ha^{-1}, and there was no significant impact on grain yield (Qiu et al., 2008). The second strategy is to achieve higher yields from the same water resources (Zhang et al.,

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2017). In this case, the way to improve WUE is by improving grain yield. Grain yield can be expressed in biomass, and the partitioning of biomass to grain (harvest index, HI; Richards et al., 2002; Reynolds et al., 2010). Under limited irrigation conditions, improving post-anthesis biomass, biomass at maturity and HI can achieve higher grain yield and WUE (Man et al., 2015; Wang et al., 2016). Grain yield was also related to increasing assimilate availability to the developing spike favoring grain number per m^2 (González et al., 2011). Improving biomass production and grain number per m^2 simultaneously and increasing the partitioning of biomass to grain is a highly promising approach to increase grain yield (Reynolds et al., 2005; Uddling et al., 2008). Different irrigation timing impacts on biomass production, HI and grain number per m^2, so as to influence grain yield and WUE (Xue et al., 2006; Zhang et al., 2013). Previous studies have shown that two irrigations (total irrigation quota was 150 mm) is adequate for winter wheat in the NCP (Li et al., 2005, 2010 ; Zhang et al., 2011), but in order to produce more grain per mm of water, the timing of two irrigations to achieve the highest grain yield and WUE needs to be further examined.

We assume the optimum two irrigation combination to achieve high grain yield and WUE will depend on coordinating pre- and post-anthesis water use and increasing post-anthesis biomass, harvest index and grain number per m^2. To verify this hypothesis, the characteristics of biomass production and grain number per m^2 under six irrigation schemes were investigated, and their relationships with grain yield and WUE were analyzed.

2. Materials and methods

2.1. Field descriptions

The experiments were conducted during the winter wheat growing seasons of 2013–2016 at Wuqiao Experimental Station of China Agricultural University at Cangzhou (37°41′N, 116°36′ E), Hebei Province, China. The soil type in the experimental field was clay-loam soil. The soil bulk density and field capacity in 0–200 cm soil layers with 20 cm increment are presented in Table 1. The organic matter, total nitrogen, hydrolysable nitrogen, available phosphorus and available potassium in the topsoil (0–20 cm) of the experimental plots were 12.1 g kg^{-1}, 1.1 g kg^{-1}, 80.6 mg kg^{-1}, 45.3 mg kg^{-1} and 122.2 mg kg^{-1}, respectively. Precipitation and daily mean air temperature in the 2013–2014, 2014–2015 and 2015–2016 growing seasons are shown in Fig. 1.

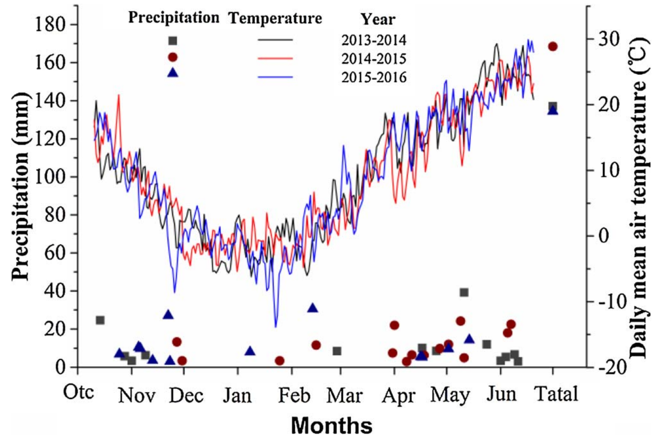

Fig. 1. Precipitation and daily mean air temperature in the 2013–2014, 2014–2015 and 2015–2016 winter wheat growing seasons.

2.2. Experimental design

The target relative soil water content of 0–200 cm soil layer was 80% field capacity before sowing, and soil water content was irrigated to 81.3%, 80.0% and 81.6% of field capacity in the 2013–2014, 2014–2015 and 2015–2016 growing seasons before sowing, respectively. Crop developmental stages were categorized using the Zadoks scale (Zadoks et al., 1974). The control (W0) had no irrigation after sowing, and there were six irrigation treatments (75 mm of each irrigation event and 150 mm of total irrigation). These were irrigation at Z30 and Z45 (late tillering and booting, TB), irrigation at Z30 and Z61 (late tillering and anthesis, TA), irrigation at Z30 and Z75 (late tillering and medium milk, TM), irrigation at Z31 and Z61 (jointing and anthesis, JA), irrigation at Z31 and Z75 (jointing and medium milk, JM) and irrigation at Z45 and Z75 (booting and medium milk, BM). Plots were irrigated evenly using surface irrigation with a 4 inch plastic-coated hose with a flow meter installed near the outlet of the hose to record the water used. The experiments were conducted in triplicate, using a randomized complete block design. Each experimental plot was 8 m × 5 m with row spacing of 0.16 m. Plots were separated by a 1 m wide zone without any irrigation to minimize the interference of adjacent plots.

2.3. Crop management

All plots were provided with 180 kg N ha^{-1},140 kg P_2O_5 ha^{-1}, 75 kg K_2O ha^{-1} and 15 kg Zn ha^{-1} before sowing. No fertilizer was applied during growth. The high yielding winter wheat cultivar 'Jimai 22' (*Triticum aestivum* L.) was used in the experiments. Winter wheat was sown on 13 October 2013, 14 October 2014 and 12 October 2015, respectively, with plant density of 525 plant m^{-2} after emergence. Wheat plants were harvested on 5–9 June 2014, 10–15 June 2015 and 4–11 June 2016, respectively.

2.4. Data acquisition and analysis

2.4.1. Estimating crop evapotranspiration

Soil samples were collected from 20 cm increments to a depth of 2 m by using a soil corer in all experimental plots. Measurements were made at sowing (Z00), beginning of anthesis (Z61) and maturity (Z91). The soil water content was determined using the oven-drying method (Gardner, 1986). Crop evapotranspiration (ET) during the growth stage was calculated according to water balance equation outlined by Li et al. (2010) as below:

$$ET = I + P - R - D \pm SW$$

Where *ET* (mm) is the crop evapotranspiration; *I* (mm) is irrigation, *P* (mm) is precipitation, *R* (mm) is surface runoff, based on the presence of beds around the plots and thus assuming that surface runoff was not significant; *D* (mm) is downward flux below the crop root zone. Soil water measurements indicated that the drainage at the site is negligible. Therefore, deep percolation was not accounted for; *SW* (mm) is the change in stored soil water (0–200 cm) between two specific stages of

Table 1
The soil bulk density and field capacity in 0–200 cm soil layers with 20 cm increment in the experimental field.

Soil layer(cm)	0 – 20	20–40	40–60	60–80	80–100	100–120	120–140	140–160	160–180	180–200
Bulk density(g cm^{-3})	1.45	1.48	1.48	1.48	1.49	1.48	1.49	1.51	1.50	1.51
Field capacity (%)	29.29	26.98	26.56	26.26	26.61	26.51	26.84	26.04	26.23	26.45