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Water use efficiency and optimal supplemental irrigation in a high yield wheat field

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ABSTRACT

Water shortage and unbalanced precipitation distribution are major problems threatening agricultural sustainability, especially winter wheat (*Triticum aestivum* L.) production, in the Huang-Huai-Hai Plain of China, and water-saving cultivation with limited irrigation is a promising technique in this region. An eight-year field study was conducted in this region from 2007 to 2015, with the same water and fertilizer management used in the sowing stage of winter wheat, which then received supplemental irrigation (SI) or no irrigation (rain-fed). The proportion of water consumption from jointing to maturity averaged 56% under rain-fed conditions, but reached 64% under the optimal SI conditions. The main water supply during the different growth periods that was suitable for achieving both high yield and high water use efficiency (WUE) had a nearly constant volume. The optimal seasonal SI amount decreased with an increasing natural water supply throughout the growing season, and its contributions to the seasonal evapotranspiration ranged from 11% to 44%. Significant regression relationships were observed among the main water supply at sowing, precipitation in different growth stages and rain-fed grain yield and between the optimal SI amounts needed from sprouting to jointing or from sprouting to anthesis and the rain-fed grain yield. These results provide important theoretical and technical support for on-demand irrigation by model forecasting. The results also indicated SI, as determined by simultaneously considering the precipitation change, soil water storage condition, and crop evapotranspiration status, is an important way to achieve high yield and conserve water in winter wheat.

1. Introduction

The Huang-Huai-Hai Plain (3HP) is one of the most important agricultural production regions in China, with a dominant annual double-cropping system of winter wheat-summer maize. The 3HP possesses approximately 25% of the total arable land and provides 71% of the nation's wheat and approximately 33% of maize production but receives less than 7% of the total water resources of China (National Bureau of Statistics of China, 2015). The annual agricultural water consumption is approximately 800–900 mm, based on multi-year observations of evapotranspiration (ET, crop water consumption) in the winter wheat-summer maize double cropping system using a large-scale weighing lysimeter (Liu et al., 2002). The average annual precipitation in this area is 556 mm and varies from 500 to 800 mm, but only 150–180 mm occurs during the winter wheat growing season, which is only approximately 25–40% of the total water requirement of winter wheat (Ren et al., 2008; Liu et al., 2011; Yuan et al., 2015). Thus, irrigation is the main way to meet the water demands for the growth, development and yield formation of winter wheat (Jha et al., 2017). Traditionally, farmers irrigated the winter wheat four to six times during the season, with a total water use of 300–400 mm, which severely jeopardized the groundwater reserves (Zhang et al., 2015a). More than 80% of the groundwater resources are exploited for crop irrigation in this area (Sun et al., 2006). The over-exploitation of groundwater sources for irrigation has created many environmental problems (Hu et al., 2010). Therefore, effective water-saving technologies need to be developed.

The timing and amount of irrigation are two critical factors for improving the water use efficiency (WUE) under limited water supply conditions. Indicators based on crop water status or soil moisture situations are usually used to determine the timing of irrigation (Zhang et al., 2015b). The crop water stress index is the most frequently used index to quantify the crop water stress and is based on the canopy surface temperature, but it can also be used for crop irrigation scheduling (Çolak et al., 2015). The threshold values of plant-available soil water content during water stress have been estimated by several researchers to identify the divergence points of physiological processes, such as leaf and stem expansion, photosynthesis, transpiration, stomatal

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Table 1
Soil nutrient contents in the 0–20 cm soil layer of experimental field before sowing of winter wheat.

Years	Experiment site	Organic matter ($g\ kg^{-1}$)	Total nitrogen ($g\ kg^{-1}$)	Hydrolysable nitrogen ($mg\ kg^{-1}$)	Available phosphorus ($mg\ kg^{-1}$)	Available potassium ($mg\ kg^{-1}$)
2007–2008	Shijiawangzi	14.6	1.00	66.40	15.40	121.58
2008–2009	Shijiawangzi	13.7	1.10	114.07	22.97	127.49
2009–2010	Shijiawangzi	13.9	1.00	89.44	29.05	121.55
2010–2011	Shijiawangzi	15.4	1.10	98.30	27.08	131.85
2011–2012	Shijiawangzi	15.1	1.00	110.40	32.71	116.12
2012–2013	Shijiawangzi	16.5	1.09	103.91	29.24	121.96
2013–2014	Shijiawangzi-Plot1	16.4	1.03	105.63	30.42	122.95
2013–2014	Shijiawangzi-Plot2	15.1	1.10	110.50	36.90	147.10
2014–2015	Nanqiu	14.0	1.00	100.10	43.90	119.90

conductance, leaf turgor pressure and leaf water potential. Additionally, several advantages for using the soil water potential as a robust descriptor of the soil water regime were described in previous studies (Dasgupta et al., 2015; Kumar et al., 2017). The amount of irrigation was generally determined by using the Pan Evaporation Method (Wakchaure et al., 2016) or the results of a series of irrigation-level experiments (Wang et al., 2016). The crop ET was estimated from irrigation, precipitation and soil water depletion. The crop ET was significantly affected by climate changes and irrigation regimes. Thus, implementing on-demand irrigation according to crop requirements should be an important way to reduce irrigation and improve the efficiency of precipitation and soil water use.

In a previous report, the soil water depletion accounted for a large proportion of the total ET, especially for the rain-fed treatment, but decreased with increasing irrigation or precipitation (Zhang et al., 2004). The seasonal ETs ranged from 275 to 480 mm for winter wheat with different precipitation (57–182 mm) seasons and irrigation schedules (Sun et al., 2010). Reducing the number of irrigation events can improve the root development in the deep soil layers, which is beneficial for both water utilization from the deep soil layers and soil water use efficiency (Xiao et al., 2007). However, other studies have suggested that with the increase of irrigation amount, the WUE initially increased and then decreased, whereas the soil water depletion continued to decline (Han et al., 2009). Panda et al. (2003) reported that the WUE of wheat was the highest when irrigation was scheduled to occur with the 45% depletion of the available soil water. Thus, coordinating the relationship between the irrigation water input and the natural water supply to improve the precipitation and soil WUE is still an urgent problem to solve.

Our previous research developed a method for determining the amount of supplemental irrigation (SI) that is required for wheat to achieve a high grain yield and WUE (Wang et al., 2013). The amount of required SI is based on the soil water content before SI, which reflects both the precipitation and the water consumed by the wheat. It has been demonstrated that an appropriate targeted soil relative water content for high grain yield and high WUE varied with the plan wetting layer setting (Guo et al., 2014; Lin and Wang, 2017). However, the underlying mechanism behind this phenomenon needs to be explored. A common standard should be established as a basis for accurate, on-demand water replenishment, rather than relying solely on the fleeting performance of the crop or soil water status. Therefore, the objectives of this 8-year study were, (1) to investigate the appropriate seasonal water supply process for obtaining a high yield and high WUE of winter wheat, (2) to reveal the relationship for the optimal seasonal SI and water supply at sowing and precipitation in different stages, and (3) to provide theoretical and technical support for exploring a new way to determine the optimal seasonal SI in winter wheat in the 3HP of China.

2. Materials and methods

2.1. Experimental site

An eight-year field study was performed in Shijiawangzi village, Yanzhou, Shandong (N35°40′, E116°41′) in the 2007–2014 growing seasons, and in Nanqiu village, Feicheng, Shandong (N35°59′, E116°52′) in the 2014–2015 growing seasons. These villages are located at the centre of the 3HP in China. The environment of this region is typical and representative of the 3HP. This region has a warm, temperate, semi-humid, continental, monsoon climate, with an annual average temperature of 12.9–13.6 °C, annual accumulated sunshine hours of 2460.9–2627.1 h, and average annual precipitation of 500–720 mm. The groundwater depth is approximately 25 m. The soil of the experiment field was silty loam. This region has a typical annual double-cropping system of winter wheat-summer maize. Winter wheat is sown in October and harvested in June of the following year. Before winter wheat sowing, we collected soil property data from the eight growing seasons, which included surface soil (0–20 cm) fertility, soil bulk density, field capacity, soil water storage and soil water content (Tables 1 and 2). The annual precipitation from 2007 to 2015 is shown in Table 2, with the data obtained from local meteorological stations. One meteorological station is 0.5 km from the Shijiawangzi experimental site, and the other station is 1.2 km from the Nanqiu experimental site.

2.2. Experimental design

The winter wheat was treated with the same water and fertilizer management at the sowing stage, and then received supplemental irrigation (SI) or no irrigation (rain-fed). Water management at the sowing stage occurred as follows: no irrigation when the soil relative water content in 0–20 cm soil layer was above 60%; when it was below 60%, irrigation was involved, and irrigation rate was determined by $I_s = 2 \times \rho b_{0\text{-}20} \times (FC_{0\text{-}20}\text{-}\theta_{m\text{-}0\text{-}20})$, where $\rho b_{0\text{-}20}$ ($g\ cm^{-3}$), $FC_{0\text{-}20}$ (%), and $\theta_{m\text{-}0\text{-}20}$ (%) were the soil bulk density, field capacity and soil water content in the 0–20 cm soil layer. The maximum irrigation rate at sowing stage was 60 mm.

The timing and amount of irrigation were set for the SI treatments after sprouting. The timing of irrigation included four levels: jointing, anthesis, jointing + anthesis, and wintering + jointing + anthesis. The amount of irrigation was dependent on the targeted soil relative water content and the plan wetting layer depth. From 2007 to 2011, the targeted soil relative water content was set to 65, 70, 75 and 80%, with a 140-cm-thick plan wetting layer. From 2011 to 2015, the targeted soil relative water content was set at 100%, and the plan wetting layer depth was set to 10, 20, 30 and 40 cm. The amount of irrigation was calculated by $CIR = 0.1 \times D_h \times \rho b \times (\theta_t\text{-}\theta_n)$, where D_h (cm) was the plan wetting layer depth, ρb ($g\ cm^{-3}$) was the soil bulk density in the plan wetting layer, θ_t ($mg\ g^{-1}$) was the targeted soil water content (field capacity × targeted soil relative water content), and θ_n ($mg\ g^{-1}$)