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Root vertical distribution is important to improve water use efficiency and grain yield of wheat

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A B S T R A C T

The winter wheat (*Triticum aestivum* L.) production of the North China Plain is threatened by increasing water shortages. Therefore, the invention of effective irrigation techniques is crucial to maintain high yields of winter wheat through improved water use efficiency (WUE). In this study, field experiments were carried out in the North China Plain region in 2012–2013 and 2013–2014. Based on the soil moisture regulation at sowing to ensure the normal emergence of the winter wheat, four supplemental irrigation (SI) regimes were set up: no-irrigation after emergence (T1), SI at jointing and anthesis (T2), SI at sowing, jointing and anthesis (T3), and SI at pre-wintering, jointing and anthesis (T4). The results showed that the root length density (RLD), root surface area density (RAD), and root weight density (RWD) in the 0–0.2 m soil layer from T2 increased rapidly after jointing and were significantly higher than those from T3 and T4 at anthesis. Those of T2 in the 0.6–0.8 m and 0.8–1.0 m soil layers were also significantly higher at anthesis. T2 was significantly higher than T1 in the photosynthetic rate (P_n) and instantaneous water use efficiency (WUE_{leaf}) of flag leaves, post-anthesis dry matter accumulation (DMA), contribution of DMA to grain (CDMA), grain yield and WUE, but lower than T1 in the pre-anthesis dry matter remobilization efficiency (DMRE) and contribution of DMR to grain (CDMR). T2 had significantly lower plant populations and dry matter at jointing, P_n and WUE_{leaf} at 28 days after anthesis, DMA and CDMA, but higher dry matter increase rate after jointing, tiller survival rate, DMR, DMRE, CDMR and WUE. The combined effect of these differences enabled T2 to have yield that was not significantly different to T4. In summary, SI at joining and anthesis that was based on suitable soil water content at sowing increased the absorbing area of roots in both deep and surface soil layers; accelerated the dry matter accumulation after jointing; increased the P_n and WUE_{leaf} of flag leaves, DMA and DMR; and finally achieved a high grain yield and higher WUE. However, excessive irrigation reduced the WUE by inhibiting the redistribution of dry matter, although the WUE_{leaf} of flag leaves was still increased.

1. Introduction

Winter wheat (*Triticum aestivum* L.) is a major crop in the North China Plain (NCP), accounting for greater than 70% of the national wheat production (Zhang et al., 2013a). The annual rainfall of the NCP ranges from 470 to 910 mm, but only 150–180 mm occurs during the winter wheat growing season, which is approximately 25–40% of the total water requirement of winter wheat (Wang et al., 2008; Liu et al., 2011). Irrigation is required for achieving high grain yield. However, multiple irrigations applied during wheat growing season has significantly reduced groundwater table (Sun et al., 2006; Wang et al., 2008; Chen et al., 2010). Wheat production is threatened by increasing water shortages (Wang et al., 2007; Zhang et al., 2010, 2013b). Therefore, it is important to develop appropriate water-saving strategies to improve water use efficiency (WUE) and maintain a high level of wheat production.

The roots of winter wheat are plastic and affected by soil water status (Zhang et al., 2015), and the enhancement of soil water use efficiency mainly depends on the development of the root system (Guan et al., 2015; Hochholdinger, 2016). The root system of winter wheat determines its ability to capture available water and nutrients (Yadav et al., 2009; White and Kirkegaard, 2010; Bengough et al., 2011), which plays an important role in the plant-soil ecosystem (Zhang et al., 2009a; Wang et al., 2014a; Xu et al., 2016). The root weight density (RWD) in the 0–1.0 m soil layer reached a maximum at the flowering stage and mostly distributed in the 0–0.4 m soil layer (Wang et al., 2014a).

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Table 1
Soil nutrition status and soil bulk density in the 0–0.2 m soil layer of the experimental field before sowing in 2012–2013 and 2013–2014.

years	Organic matter ($g\ kg^{-1}$)	Total nitrogen ($g\ kg^{-1}$)	Hydrolysable nitrogen ($mg\ kg^{-1}$)	Available phosphorous ($mg\ kg^{-1}$)	Available potassium ($mg\ kg^{-1}$)	Soil bulk density ($t\ m^{-3}$)
2012–2013	16.50	1.09	103.91	29.24	121.96	1.60
2013–2014	16.39	1.03	105.63	30.42	122.95	1.40

Irrigation regimes strongly influence the density and depth of roots (Wang et al., 2004). Water stress will restrict root growth and distribution in the soil (Gajri et al., 1989), and reduce the root length density (RLD) (Li et al., 2010). It has been found that total root dry weight, volume, length and number of branches reduce with decreasing irrigation times (Zhang et al., 2009a). However, limited irrigation can stimulate roots to grow into deeper soil layers and thus enhanced the uptake of soil-stored water from the subsoil layers (Wang et al., 2014a). Li et al. (2010) reported that one-time irrigation at jointing resulted in the highest RLD in > 0.3 m deep soil layers. Greater root biomass was significantly associated with greater shoot biomass, which contributed to higher grain yields and WUE (Zhang et al., 2009b). However, the relationships between the morphology and distribution of root and the grain yield and WUE of wheat remains an important topic of discussion.

WUE is a key physiological parameter indicating the ability of crops to conserve water in a water-scarce region because it combines drought resistance and high potential yield (Fang et al., 2010; Zhang et al., 2010; Xu et al., 2016). Appropriate deficit irrigation does not necessarily reduce crop production and can result in high grain yield and WUE in wheat (Zhang et al., 2006; Fereres and Soriano, 2007). Xu et al. (2016) suggested that 60 mm irrigation applied at elongation was the best irrigation scheme for efficient water use and relatively high yield in winter wheat, but others argued that 120 mm irrigation during the winter wheat growing season could produce a reasonable grain yield and WUE (Bian et al., 2016). Du et al. (2010) reported that the maximum grain yield of winter wheat was achieved when 84% of maximum crop-water requirements were applied. Therefore, the frequency and amount of irrigation could be reduced to increase dry matter accumulation, promote grain-filling rate, and improve the yield and WUE of wheat (Zhang et al., 2006). Many studies attributed the yield and WUE improvement to the increase of water uptake and utilization from the deep soil layers (Johnson and Davis, 1980; Guo et al., 2016) because limited irrigation can stimulate roots to grow into deeper soil layers (Wang et al., 2014a; Xu et al., 2016). However, the shallow root system is required for absorption of nutrients that are mostly concentrated in the upper layers of soil (Manske and Vlek, 2002); furthermore, the superficial root parts may also be beneficial for capturing rainfall that does not infiltrate to the deeper soil layers (Ehdaie et al., 2012). Simultaneously promoting the absorption and utilization of the water from the deep soil layers and the rich nutrition from the upper soil layers is crucial for increasing in WUE.

In this study, a method for determining the amount of supplemental irrigation (SI) required of wheat to achieve high grain yield and WUE was adopted, in which, the amount of SI is based on the soil water content before SI, which reflects both the precipitation and water consumption by the crop (Wang et al., 2013). Four SI regimes were designed to (1) determine the effects of the SI regimes on root growth and distribution; (2) clear the response of gas exchange characteristics of leaves, dry matter accumulation and redistribution, grain yield and WUE to SI regimes; and (3) clarify the relationships between wheat root distribution and wheat production.

2. Materials and methods

2.1. Experimental site

The field experiment was performed from 2012 to 2014 in Yanzhou (116°41′E, 35°42′N), Shandong Province, China. This experimental area belongs to temperate, continental, monsoon climate with an average annual temperature of 13.6 °C and an annual precipitation of 621.2 mm. Approximately 40% of the precipitation occurs during the winter wheat growing season which is from October to June. The average annual groundwater level is 25 m. The soil of the experimental field was silty loam, and the previous crop was corn (*Zea mays* L.). The organic matter, total nitrogen, hydrolysable nitrogen, available phosphorous, and available potassium in the 0–0.2 m soil layer of the experimental field before sowing were 16.50 $g\ kg^{-1}$, 1.09 $g\ kg^{-1}$, 103.91 $mg\ kg^{-1}$, 29.24 $mg\ kg^{-1}$, and 121.96 $mg\ kg^{-1}$ in 2012–2013 and 16.39 $g\ kg^{-1}$, 1.03 $g\ kg^{-1}$, 105.63 $mg\ kg^{-1}$, 30.42 $mg\ kg^{-1}$, and 122.95 $mg\ kg^{-1}$ in 2013–2014, respectively. The soil bulk density of 0.2 m soil layer was 1.60 $t\ m^{-3}$ in 2012–2013 and 1.40 $t\ m^{-3}$ in 2013–2014 (Table 1). The field capacity and relative water content in the 0–2.0 m soil layers of the experimental field before sowing are listed in Table 2. The precipitation amount in different growth stages of winter wheat and the seasonal precipitation in 2012–2013 and 2013–2014 are shown in Table 3.

2.2. Experimental design

Jimai 22, one of the most widely planted commercial winter wheat cultivars in the NCP, was used for this study. Four SI regimes were set up (Table 4) in 2012–2013: no-irrigation after emergence (T1), SI at jointing and anthesis (T2), SI at sowing, jointing and anthesis (T3), and SI at pre-wintering, jointing and anthesis (T4). The SI brought soil water content in the 0–1.4 m soil layer to 85% of field capacity at sowing and pre-wintering stages, and to 70% of field capacity at jointing and anthesis stages in 2012–2013, according to our previously published method (Wang et al., 2013). In 2013–2014, the irrigation period of four SI regimes was consistent with previous year, but the SI brought soil water content in the 0–0.2 m soil layer to 100% of field capacity at pre-wintering, jointing and anthesis stages. This was based on the distribution of wheat root and infiltration rule of irrigation water in soil, in order to save the time and manpower required for measuring the soil water content before irrigation and to facilitate the application of SI technology in wheat production. In 2013–2014, irrigation was applied

Table 2
Field capacity and relative soil water content in the 0–2.0 m soil layers of the experimental field before sowing.

Soil layer (m)	2012–2013 Field capacity (%)	2012–2013 Relative soil water content (%)	2013–2014 Field capacity (%)	2013–2014 Relative soil water content (%)
0–0.2	24.57	64.13	29.04	32.62
0.2–0.4	22.81	70.30	27.82	31.12
0.4–0.6	27.20	64.06	26.09	46.82
0.6–0.8	23.66	71.76	26.43	62.28
0.8–1.0	24.52	75.65	27.71	71.23
1.0–1.2	21.75	94.97	26.90	71.26
1.2–1.4	22.76	95.25	24.08	75.20
1.4–1.6	22.90	94.31	25.08	73.86
1.6–1.8	22.70	96.94	24.48	76.46
1.8–2.0	22.81	98.06	24.28	77.82
mean	23.57	82.54	26.19	61.87