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Presowing fertigation effects on soil moisture absorption and consumption of cotton in arid regions

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ABSTRACT

To increase the yield and water-use efficiency of cotton in arid regions, irrigation and fertilizer management must be optimized. This study evaluated the effects of two irrigation levels (i.e., with (W_{80}) and without (W_0) presowing irrigation) combined with two basal fertilization methods (i.e., surface application (F_{10}) and deep application (F_{30})) on soil water absorption and transport, and relationships with water-use efficiency. Our results showed significantly positive relationships between water-use efficiency and the root surface area in the 0–30 cm soil layer (RSA-30), root vigor in the 0–30 cm soil layer (RV-30), root vigor in the 60–80 cm soil layer (RV-80), the leaf transpiration rate, stomatal conductance, sap flow, and water productivity. Principal component analysis showed that the $W_{80}F_{10}$ treatment initially positively influenced RSA-30, RV-30, and RV-80 and that these parameters affected the leaf transpiration rate, stomatal conductance, sap flow, and leaf area (i.e., the main transpiration area), which finally influenced water productivity and water-use efficiency. In addition, the $W_{80}F_{10}$ treatment increased the ability of aerial parts to compete for water after 69 days after emergency. These findings indicate that the combination of presowing irrigation and basal fertilizer surface application can enhance the ability of aerial parts to compete for water and increase water-use efficiency by promoting water absorption and consumption after the full flowering stage. This research provides valuable information on agricultural management in aridregions.

1. Introduction

Water stress limits crop yield more than all other biotic and abiotic factors combined (Lambers et al., 2008; Walter et al., 2011). The frequency and magnitude of regional drought periods have been increasing since the 1970s, and the situation is projected to worsen in many parts of the world (Schar et al., 2004; Trenberth et al., 2003). Therefore, increasing water-use efficiency (WUE) or improving plant resistance has become a basic research topic related to sustainable agricultural development and agricultural-ecological balance (Beltrano et al., 1999; Zhao et al., 2014).

As a direct response to water shortages or limitations in arid and semiarid areas, WUE has attracted considerable attention in terms of improving the biological water-saving potential of crops through water-nutrient management (Huang and Eissenstat, 2000; Zheng et al., 2011; Gopalakrishnan et al., 2014). Many studies (Kim et al., 2007; Luo et al., 2014) have shown that the limiting factors of WUE mainly include water absorption, transport, consumption, and advantage. Therefore, to evaluate the biological water-saving potential of crops, we need to consider four aspects. First, roots are the first organs that come into

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Abbreviations: BWP, water productivity of bud and boll ($g\ cm^{-3}$); DAE, days after emergence (d); Fs, sap flow ($g\ d^{-1}$); F_{10}, basal fertilization surface application; F_{30}, basal fertilization deep application; Gs, stomatal conductance ($mol(H_2O)m^{-2}\ s^{-1}$); LA, leaf area (cm^2); MCR, soil moisture consumption rate ($cm^3\ plant^{-1}$); RSA, root surface area (cm^2); RSA-30, root surface area in 0–30 cm soil layer (cm^2); RSA-80, root surface area in 60–80 cm soil layer (cm^2); RV, root vigor ($ug\ g^{-1}\ FW\ h^{-1}$); RV-30, root vigor in 0–30 cm soil layer ($ug\ g^{-1}\ FW\ h^{-1}$); RV-80, root vigor in 60–80 cm soil layer ($ug\ g^{-1}\ FW\ h^{-1}$); RWP, water productivity of root ($g\ cm^{-3}$); SM, soil moisture content ($g\ cm^{-3}$); Tr, transpiration rate ($mol(H_2O\ m^{-2}\ s^{-1}$); TWP, total water productivity ($g\ cm^{-3}$); VWP, water productivity of stem and leaf ($g\ cm^{-3}$); WUE, water use efficiency; W_{80}, presowing irrigation; W_0, without presowing irrigation; W_0F_{10}, the couple of no watered deep soil layer and base fertilizer surface; W_0F_{30}, the couple of no watered deep soil layer and base fertilizer deep; $W_{80}F_{10}$, the couple of watered deep soil layer and base fertilizer surface; $W_{80}F_{30}$, the couple of watered deep soil layer and base fertilizer deep

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contact with soil water, and water-nutrient management mainly adjusts root development, root distribution and root physiological activity (Jackson et al., 1990; Wasson et al., 2012; Luo et al., 2014; Dai et al., 2015). Such management changes the water absorption of the root, subsequently affecting WUE (Lopes and Araus, 2006; White, 2013). Second, water-nutrient management mainly affects water transport by changing the transpiration rate and area (Maricle et al., 2009; Chen et al., 2017b); these changes potentially adjust the transport of water in the plant and adjust water use and consumption (Maricle et al., 2009; Li et al., 2014). Lastly, the central aspects of WUE in crop water-use-systems are water consumption and use, whereas the transpiration area (i.e., leaf area, LA), stomatal conductance (Gs), the leaf transpiration rate (Tr), water productivity (WP, i.e., water-use ability) and WUE are the central aspects of crop water consumption and use (Kang et al., 1998, 2000; Du et al., 2010). Water-nutrient management can adjust LA (i.e., transpiration area) as well as leaf Gs and Tr (Luo et al., 2014; Li et al., 2014; Chen et al., 2017a,b; Chen et al., 2018), though Gs and Tr are positively related to WUE (Kang et al., 1998, 2000; Du et al., 2010; Luo et al., 2014), and limiting Gs can reduce Tr and subsequently increase WUE (Kang et al., 1998, 2000; Kang and Zhang, 2004; Dodd, 2009; Du et al., 2010). Therefore, optimizing root morphology and physiological traits through water-nutrient management may promote water absorption, increase water transpiration efficiency, or balance the relationship between water consumption and use; furthermore, this approach might be a promising biological water-saving method.

Cotton (*Gossypium hirsutum* L.) is one of the most important fiber-producing plants. The cotton yield in Xinjiang accounts for 60% of the total cotton yield in China and represents 18% of the total global cotton yield (data obtained from the China Cotton Fair Examination website). However, the lack of water resources significantly impacts the agricultural and ecological environments (e.g., affecting the susceptibility of cotton to light, temperature, and moisture) and the agricultural production (i.e., affecting the cotton yield and quality). Therefore, it is crucial to develop methods that promote the biological water-saving potential of cotton to reduce water limitations. Our previous studies have shown that the deep-water layer, which results from presowing irrigation or snow melt, has the potential to direct root growth toward the deep soil layer for moisture, which supports the overall WUE (Luo et al., 2012, 2014). Basal fertilization can support cotton root development before the full flowering stage (i.e., generally, root development occurs before the full flowering stage) and increase the available nutrients in the soil layer (Garrido-Lestache et al., 2004; Shen and Li, 2011). In addition, roots tend to grow toward soil nutrients; thus, basal fertilizer application might modify the root distribution in the soil profile and increase the root competitive ability for moisture in the soil layer with evaporation (Zhang, 2013), improving WUE.

The objective of this study was to determine the effects of presowing irrigation and basal fertilization management on soil water content, root morphophysiological traits, Fs, Gs, Tr, LA, and WUE. We also evaluated the contribution of water absorption, transport, consumption, and use to WUE and the competitive strategies organs use to obtain water.

2. Materials and methods

2.1. Experimental site

The experiments were conducted during 2015 and 2016 at the experimental farm of Shihezi University (latitude: 45°19′N, longitude: 86°03′E), and the study focused on cotton *cv*. Xinluzao 45 (*G. hirsutum* L.). Cotton was grown in polyvinyl chloride (PVC) tubes (diameter: 30 cm; the tubes consisted of three stacked sections, and each section was 40 cm high for a total column height of 120 cm), and the PVC tubes were buried so that only 10 cm remained aboveground (i.e., buried width: 35 cm, buried height: 110 cm). The bottom of the tube was covered with a wire mesh that was fine enough to hold soil while still allowing water to pass through. Clay loam soil was collected from the field station and passed through a 2 mm sieve; these soil samples were packed into the PVC tubes in increments from 0.1 m to 1.2 m and were then air dried. The bulk density of the soil was 1.43 g m^{-3}. The soil composition was purple clay loam (pH: 7.6), with 1.45 g (total N) kg^{-1}, 0.23 g (P_2O_5) kg^{-1}, 149 g (total K) kg^{-1}, and 12.5 g (organic matter) kg^{-1}. The maximum and minimum temperatures were 26.4 and 9.4 °C, respectively, in 2015 and 33.6 and 2.9 °C, respectively, in 2016. The mean precipitation was 34 mm in 2015 and 16.5 mm in 2016.

2.2. Experimental design

A randomized complete block design was employed for four treatments that each had 4 replicates. For each treatment, twelve tubes were vertically buried in the field. The two water treatments included presowing irrigation ($\mathbf{W_{80}}$, watered with 0.28 m^3 (80 ± 5% of field capacity) per tube before sowing) and no presowing irrigation ($\mathbf{W_0}$, no water was applied over the entire depth of the tube). Based on the results from our previous study that investigated the fertilizer production requirement of cotton (i.e., more than 2300 kg ha^{-1} settled fertilizer), basal fertilizer (2.76 g of N, 9.36 g of P_2O_5, 6.38 g of K_2O per tube) was applied at two fertilization depths. Surface application ($\mathbf{F_{10}}$) referred to sufficient basal fertilizer in the 10–20 cm layer before sowing, and deep application ($\mathbf{F_{30}}$) referred to sufficient basal fertilizer in the 30–40 cm layer before sowing. Nitrogen was applied with a ratio of basal fertilizer to topdressing of 1:4. Phosphorus and potassium were supplemented as basal fertilization. Urea ($CO(NH_2)_2$, 46.0% N) was used for nitrogen at a rate of 13.8 g per tube, while 18 g of monopotassium phosphate (i.e., (KH_2PO_4), 52.0% P_2O_5 and 35.4% K_2O) was used per tube for the application of the aforementioned amounts of P_2O_5 and K_2O.

On April 25 and May 1 of 2015 and 2016, four seeds were sown at a depth of 3 cm in each tube. The seeds were spaced 10 cm apart in one direction and 20 cm apart in the other direction. Drip laterals (Beijing Lvyuan Inc., China) were installed on top of the tubes, and one emitter was fixed at the center of each tube. To reduce evaporation, the top of the tube was covered with polyethylene film. Each pot was drip-irrigated once every four days. The total amount of water supplied to the plants in the different treatments was 434 mm each year. Standard local pest control measures were adopted. Soil water content (in 2016), root morphological factors (in 2015 and 2016), root vigor (RV) (in 2016), LA (in 2015 and 2016), Gs (in 2016), Tr (in 2016), WP (in 2016) and WUE (in 2016) were assessed at 39, 54, 69, 84, and 99 days after emergence (DAE), while Fs (in 2016) was assessed from 51 to 99 DAE.

2.3. Soil water content

The amount of irrigation during the growth period was determined by measuring the soil moisture (SM) content in the 0–40 cm layer by Time Domain Reflectometry (TDR) (Thompson et al., 2016). The stoving method was used to assess the change in SM content in the 0–120 cm layer was determined at sampled roots and at a time point mid-way between two root samplings. When roots were sampled, fresh soil from each soil layer was quickly collected (in 2016, the soil layer was divided into 10 cm segments) for SM content analysis. Additionally, soil drilling (with a diameter of 2 cm, which has a smaller effect on the roots of cotton plants) was employed to determine the SM content of each soil layer was determined at a time point mid-way between two root samplings.

2.4. Root surface area (RSA) and root vigor (RV)

Three tubes (each treatment) were carefully removed from the ground and cut into 20 cm segments in 2015 and 10 cm segments in 2016; the cuts started from the top of the columns. The segments were immersed in water for 1 h, and the roots were placed on a 0.5 mm sieve and rinsed with running water. Plant debris, such as weeds and dead