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Spatial distribution of soil moisture, soil salinity, and root density beneath a cotton field under mulched drip irrigation with brackish and fresh water

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ABSTRACT

Root systems play a vital role in soil-plant interactions. The dynamics and distributions of soil moisture content (SMC), soil salinity, and cotton (*Gossypium hirsutum* L.) root density under mulched drip irrigation are complex and their interactions are not well understood. The aim of this study is to describe these dynamics and distributions and to evaluate their impacts on cotton above-ground growth and yield during two-year field experiments in a cotton field under mulched drip irrigation with brackish and fresh water. Significant differences were observed for the distributions of SMC, soil salinity, and root length density (RLD) in the root zone for brackish water irrigation treatment (BWT) and fresh water irrigation treatment (FWT). The average SMC and soil salinity in the root zone were higher for BWT than for FWT. The spacing of irrigation lines also had measurable impacts. SMC was less variable when irrigation spacing was small (narrow rows) than beneath wide rows. SMC for BWT and FWT decreased after irrigation due to root water uptake; simultaneously, salt concentration increased, especially in regions where RLD was relatively high. More roots were observed growing in the mulched narrow and wide rows than in the no-mulch zone. Roots were concentrated in the shallowest 30 cm. Our study indicated that the average values of the EC_e (electrical conductivity of soil saturation extract) in the root zone after BWT irrigation were higher than the published threshold value for optimal cotton yield. The average RLD, shoot dry weight and yield for BWT were observed to be lower than those of FWT as a result of the elevated soil salinity associated with BWT.

1. Introduction

Water shortage and soil salinization are the two main factors limiting sustainable agriculture in many arid and semiarid regions in the world (Angus and van Herwaarden, 2001; Chen et al., 2010a; Kang et al., 2017). There is significant interest in using low quality irrigation water that has elevated salinity to meet increased water demands in these regions (Cetin and Kirda, 2003; Bustan et al., 2004; Rozema and Flowers, 2008; Selim et al., 2013; Wang et al., 2014). Southern Xinjiang in Northwest China is a typical example of such an arid region (Wang et al., 2014). Shallow brackish water with total dissolved solids (TDS) greater than 2–3 $g L^{-1}$ is widespread and exhibits great potential for agricultural irrigation to compensate for a lack of available fresh water in Xinjiang (Chen et al., 2010a; Wang et al., 2011). Meanwhile, mulched drip irrigation, using plastic mulch in conjunction with drip irrigation, has been applied increasingly in Xinjiang since the 1990s (Liu et al., 2012; Dai and Dong, 2014; Zhang et al., 2014). When using brackish water, mulched drip irrigation can reduce evaporation and deep percolation, maintain constant high soil moisture content (SMC) in the root zone, increase soil temperatures, and reduce salt leaching (Mmolawa and Or, 2000; Ibraginmov et al., 2007; Liu et al., 2012; Li et al., 2015; Tan et al., 2017; Zhang et al., 2017). In recent years, there is growing interest in mulched drip irrigation with brackish water for cotton (*Gossypium hirsutum* L.), a salt-tolerant crop (Liu et al., 2012; Wang et al., 2014; Ning et al., 2015). However, brackish water may contribute to soil salinization (Mmolawa and Or, 2000). The resulting excess soil salinity can reduce osmotic potentials to the point that crop roots cannot uptake enough water, even causing crop failure (Maas and Hoffman, 1977; Khan et al., 2004). Therefore, it is important to use brackish water efficiently to support agricultural irrigation while

Abbreviations: BWT, Brackish water irrigation treatment; DAS, days after sowing; DW, dry weight; EC, electrical conductivity; FWT, fresh water irrigation treatment; IWP, irrigation water productivity; RLD, root length density; SMC, soil moisture content; SWS, soil water storage; TDS, total dissolved solids

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avoiding secondary salinization.

Root systems play a vital role in soil-plant interactions (Gregory, 2006; Zhang et al., 2009). Crops absorb almost all water and nutrients through their root systems. A well-developed root system is essential for increasing the irrigation water productivity (IWP) and crop yield (Min et al., 2014; Feng et al., 2017). Root system architecture is highly influenced by the soil environmental conditions, including the soil moisture and soil salinity distributions (Malamy, 2005; Gao et al., 2014; Kong et al., 2012; Ning et al., 2015). Crop root systems can optimize their architecture to absorb a greater proportion of soil moisture and nutrients from parts of the soil profile with low salinity (Coelho and Or, 1999; Dong et al., 2010; Green and Clothier, 1998; Hodge et al., 2009). Simultaneously, roots affect root zone water and solute dynamics (Mmolawa and Or, 2000). After irrigation, soil water is lost due to root water uptake or evaporation from the soil while most of the salts are left behind. This leads to redistribution of SMC and accumulation of soil salinity in the root zone (Li et al., 2015). It is thus important to investigate variations in SMC, soil salinity and root distribution, and to study the regulation of soil-root interactions under mulched drip irrigation to improve fertigation schedules for better mulched drip irrigation management.

In recent years, soil water flow and salt transport under mulched drip irrigation have been studied through experimentation (e.g. Zhang et al., 2014; Li et al., 2015) and with simulation models (e.g. Chen et al., 2010a; Selim et al., 2013; Wang et al., 2014). For example, researchers have investigated the effects of soil texture (Hu et al., 2011), plant and drip line arrangements (Ning et al., 2015), irrigation water quality (Wan et al., 2007) and irrigation water amount and frequency (Liu et al., 2013) on soil water flow and salt movement. Results generally show that the SMC is affected by drip irrigation with plastic mulch mainly in the shallow subsurface (Liu et al., 2013; Li et al., 2017). Average salinity in the root zone increases during the growing season when using brackish water irrigation, as the excess salts accumulate in the root zone under deficit irrigation (Chen et al., 2010a; Liu et al., 2013; Zhang et al., 2014). Additionally, recent studies have discussed how SMC and soil salinity patterns affect root system growth and distribution. It is reported that cotton root growth under drip irrigation with plastic mulch was focused directly below the drip lines. This localized growth occurs because the shallow subsurface near emitters receives sufficient water and salinity is reduced by continual leaching (Mai et al., 2013; Huang et al., 2015).

Irrigation water quality (e.g. brackish or fresh water) under mulched drip irrigation significantly affects the distributions of SMC, soil salinity and root length density (RLD) (Chen et al., 2010a; Liu et al., 2013; Huang et al., 2015). The specific spatial distributions of SMC and soil salinity depend on irrigation events, root water uptake and evaporation from the bare soil surface (Li et al., 2015). Crop root architecture is moderated by these changing soil environmental conditions in the root zone (Hodge et al., 2009). Meanwhile, the root distribution feeds back to influence SMC and soil salinity dynamics (Coelho and Or, 1999). Understandably, these dynamics and the associated spatial distributions are complex and difficult to predict. The dynamics and the detailed distribution of roots are also difficult to monitor (Chen et al., 2017a; Li et al., 2017). To the best of our knowledge, no experimental studies have characterized these dynamics and distributions under mulched drip irrigation with brackish and fresh water.

The main objectives of this study were to: (i) monitor the spatial distributions of SMC and soil salinity under mulched drip irrigation with brackish and fresh water, (ii) characterize cotton root density and its response to the SMC and soil salinity conditions, and (iii) compare the cotton above-ground growth and yield under mulched drip irrigation with brackish and fresh water.

2. Materials and methods

2.1. Experimental site

The study was carried out in a cotton field at the Irrigation Experimental Station of the Ministry of Water Resource of the People's Republic of China in Korla, Xinjiang. The research area is located in an alluvial plain of the Peacock River, Tarim Basin, in the arid southern part of Xinjiang (41°35'N, 86°10'W). It is 901 m above mean sea level and is classified as a continental desert climate with an average annual precipitation of only 58 mm and maximum potential evaporation of 2788.2 mm. The mean annual temperature is 11.5 °C with a minimum of −30.9 °C and a maximum of 42.2 °C. The mean annual wind speed is 2.4 m s^{-1} with a maximum wind speed of 22 m s^{-1} (Li et al., 2016). The depth to the water table in the cotton field during the growing season in 2014 and 2015 ranged from 3.97–6.10 m and 6.57–7.45 m, respectively. The soil texture, which was relative homogeneous, was loamy sand. The bulk density was 1.59 g cm^{-3} and percentages of sand, silt, and clay were 76.17, 20.04, and 3.79, respectively.

2.2. Experimental treatments and procedures

Cotton (*Gossypium hirsutum* L.) cv. Xinluzhong 35 was sown on 3 May 2014 and 23 April 2015 at a density of 24 seeds m^{-2} and mulched with degradable plastic film. Drip lines were set following "one mulch, two drip lines, and four rows of cotton plants" (Fig. 1), which indicated that there were two drip lines beneath each mulch, and each mulch contained four rows of cotton plants. The wide row zone, narrow row zone and no-mulch zone are defined according to the location of the cotton plants (Fig. 1). The width of plastic film was 110 cm, the widths of the wide row zone, narrow row zone, and no mulch zones were 50, 20, and 40 cm, respectively (Fig. 1). Drippers along each drip line were separated by 30 cm, while the cotton plants along each row were spaced 10 cm apart. Two water sources, brackish water from a local deep well and fresh water from the Peacock River, were used to irrigate cotton plants during the growing season. The two irrigation treatments were arranged in a randomized block design with three replicates for each treatment. Each plot was 10 × 18 m and adjacent plots were separated by 1 m to eliminate the effect of lateral movement of soil water. The total dissolved solids (TDS), electrical conductivity (EC) and main elemental contents of the brackish and fresh water are presented in Table 1. Quantities of applied irrigation water and their distribution during the entire cotton growing season followed traditional irrigation patterns of cotton in the research area (Table 2). In addition, flood irrigation with fresh water was used after the harvest during the following spring. The total amount of irrigation water applied outside of the growing season was 225 mm. During the cotton growing season, total precipitation was 15.6 and 49.4 mm in 2014 and 2015, respectively. In which, the highest precipitation event was 2.2 and 6.6 mm in 2014 and 2015, respectively. The background surface soil (20 cm) contained 23.81 mg kg^{-1} total N, 15.23 mg kg^{-1} available P, 107.56 mg kg^{-1} available K, with an EC_e (electrical conductivity of soil saturation extract) of 3.85 mS cm^{-1}. To meet the cotton plant nutrient requirements, 1800 kg hm^{-1} organic fertilizer ($N + P_2O_5 + K_2O \geq 5\%$, organic matter ≥ 30%), 300 kg hm^{-1} diammonium phosphate ($N + P_2O_5 \geq 64\%$) and 150 kg hm^{-1} potassium fertilizer ($K_2O \geq 51\%$, Mg ≥ 2%) were applied as the base fertilizers before plowing. During the growing season, 266.4 kg hm^{-1} urea (N ≥ 46%) was applied by fertigation (Table 2).

2.3. Cotton root measurements

Root samples were collected four times on 64, 74, 106 and 126 days after sowing (DAS) for both BWT and FWT in 2014. Root samples were collected by the monolith method (Böhm, 1979). The spatial layout of root sampling was designed according to the cotton plant and drip line