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Drip irrigation lateral spacing and mulching affects the wetting pattern, shoot-root regulation, and yield of maize in a sand-layered soil

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ABSTRACT

Soil with a 20–60 cm thick subsoil (60–90 cm below the surface) sand layer has been recently reclaimed to exploit its grain production potential in an arid region in northwest China. A 2-year field study was conducted in the Hetao irrigation district to investigate the effects of lateral spacing and soil mulching methods under drip irrigation on the soil moisture, NO_3^-, shoot-root regulation, and water use efficiency (WUE) of spring maize. The Christiansen uniformity coefficient (C_{us}) was adopted to evaluate soil moisture and NO_3^- distribution, which was calculated with soil water content and NO_3^- concentration. The four studied treatments consisted of two irrigation lateral-spacings (A1: 1.0 m, A2: 0.5 m) and two film-covering modes (M1: fully mulched, M2: partially mulched) were arranged.

Soil moisture was most affected by mulch coverage (full or half surface coverage) under low frequency irrigation lateral spacing (adjacent to or between crop rows) under high frequency irrigation. Lateral spacing exerted a notable influence on soil moisture at a 20 cm depth, while the mulching method influenced soil moisture mainly at 40 cm. Irrigation frequency and close lateral spacing can effectively enhance C_{us}. Based on our observations, a decrease in the C_{us} of soil NO_3^- may occur under frequent fertigation, particularly when irrigation laterals are between crop rows. The mulching method can play an important role in improving the concentration and C_{us} of soil NO_3^-, while the A2 treatments can slow the decrease of the C_{us} of soil NO_3^- under frequent fertigation. Root length density (RLD) under A1 treatments were lower close to lateral while higher away from lateral than A2 treatments. Close lateral spacing can result in high hundred gain weight (HGW) and high harvest index (HI) while exerting a more conspicuous effect than the mulching method by extending the grain filling stage.

Frequent fertigation (i.e. once every three days) after jointing is preferentially recommended in a sand-layered field. A1M2 should be chosen for higher HI and low cost. If frequent fertigation is infeasible, A2M1 can be a good choice under low frequency fertigation.

1. Introduction

Mulched drip irrigation (MDI) has been widely employed in arid and semiarid regions for crop cultivation (Liu et al., 2013) to accurately supply water and fertilizer in the soil in conjunction with soil evaporation reduction (Vázquez et al., 2006). However, MDI may cause premature senescence and decreased yield. Li et al. (2001) suggested that a shortage of tissue carbohydrates caused grain yield reduction due to the extravagant consumption of water and nitrogen during the vegetative period under mulch conditions. Hu et al. (2009) found that MDI was unfavourable for root growth because of excessive soil moisture and reduced soil aeration. Li (2006) reported that root distribution was restricted by the wetting pattern, and fine roots were concentrated within the wetted volume. Additionally, the side of the bed, away from the drip

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tube, can become extremely hot and dry, which creates conditions unfavourable for root growth as the season progresses (Bar-Yosef et al., 1980). Mai and Tian (2012) determined that cotton prematurely senesced under drip irrigation due to a shortage of soil nutrients as a result of an excessive shoot-to-root biomass ratio ($B_{c/r}$). Based on the cited research, $B_{c/r}$ regulation through wetted region management should be carefully considered under drip irrigation.

The frequency, rate, and duration of water application and the placement of drip tubing are irrigation parameters that determine wetting zone dimensions (Skaggs et al., 2004). Wetted soil volume is also strongly affected by soil hydraulic properties (El-Hendawy et al., 2008). Several approaches based on these theories have been used to estimate wetting zone dimensions, including the numerical HYDRUS model, the analytical WetUp software program, and several empirical models (Kandelous and Šimůnek, 2010; Malek and Peters, 2011; Al-Ogaidi et al., 2016). Commonly, the water application rate in the field ranges from 1 to 4 l/h, and the surface wetted radius (R) and the vertical advance of the wetting front (Z) display little difference within this range (Palomo et al., 2002; Li et al., 2004). In addition, over-frequent water application is costly. Regarding the frequency and rate of water application, lateral spacing is considered a more effective and convenient parameter for wetted region management under drip irrigation at the field scale (Cai et al., 2002; Bozkurt et al., 2006). Moreover, Lamm et al. (1997) considered that increasing the spacing of dripline laterals could decrease the high investment costs of drip irrigation. However, excess lateral spacing was unsuitable for drip-irrigated corn production in the Mediterranean Region of Turkey due to long irrigation times and probable deep percolation losses (Bozkurt et al., 2006). Chen et al. (2015) found that a lateral spacing of 60 cm was the optimum for drip-irrigated spring wheat production in northern Xinjiang, where annual precipitation is less than 200 mm, and annual pan evaporation is over 2000 mm.

Soil NO_3^- concentrations respond to water applications which subsequently affect the water and nutrient uptake of crops (Gorska et al., 2008). Bar-Yosef and Sheikholslami (1980) found that NO_3^- was concentrated in the wetted soil zone between drip emitters in both a clay and a sandy soil. The NO_3^- concentration in the wetted soil zone of clay was lower than irrigation water concentration, while no difference in NO_3^- concentration between the wetting zone and irrigation water in sandy soil was observed. Cook and Sanders (1990) confirmed that in soil with a rapid infiltration rate, NO_3^- levels in the centre of the bed were always low and exhibited the highest concentration in the areas of the bed most distant from the drip tube. In contrast, in soils with the slower infiltration rate, NO_3^- concentrations were more uniform throughout the bed, with the highest concentrations in the bed centre.

In recent years, land with a soil profile including a 20–60 cm thick subsurface, sand layer randomly distributed between the 40–100 cm soil depths, has been reclaimed in Hetao Irrigation District (40°19–41°18N, 106°20–109°19E), one of the three largest irrigation districts in China and is located in the arid region of northwest China. Utilizing the abundant water resources of the Yellow River, extensive irrigation is generally practiced in the district. This practice results in low water use efficiency and the substantial nonpoint source pollution of the drainage receiving system (Guo et al., 2014). Soil with subsurface sand layer with a high water permeability may amplify these problems (Walter et al., 2000). Therefore, impermeable media, such as asphalt (Hansen and Erickson, 1969) or polyethylene foil (Guber et al., 2015), are laid within the soil profile to prevent water loss through deep percolation in sandy substrates. However, film-bottomed tillage (FBT) is costly and disturbs the deep soil, which may destroy the natural environment of the soil and its population of soil biota and microorganisms (Nakamoto and Tsukamoto, 2006; Miura et al., 2008). In addition, FBT may obstruct groundwater recharge to sustain crop evapotranspiration.

Therefore, we assumed that lateral spacing and mulching modes might modulate the shape, moisture, and NO_3^- distribution of the wetted soil volume, thus affecting the $B_{c/r}$ and yield of crops. Outflow emitter uniformity is typically used to evaluate irrigation performance. However, soil moisture uniformity is the goal of drip irrigation system design (Burt et al., 1999), which has been less studied in the literature. Therefore, the objectives of this study were (1) to determine the effect of lateral-spacing and film-covering modes on the wetting pattern, soil moisture and NO_3^- concentration distributions; (2) to investigate how shoot-root growth, yield, and irrigation water use efficiency (IWUE) are affected by different lateral-spacing and film-covering modes in mulched, drip-irrigated maize in a soil including a subsoil sand layer under arid climatic conditions; and (3) to provide advice on lateral spacing and mulching method under various irrigation frequencies in sand-layered field.

2. Materials and methods

2.1. Site and climatic conditions

The experiment was conducted in 2014 and 2015 at the Shuguang Irrigation Research Station in the Hetao Irrigation District, western Inner Mongolia autonomous region, China (40°43N, 107°13E, 1042 m asl). This region is characterized as an arid continental climate, with an average annual rainfall of 135 mm concentrated in June through September. The mean annual pan evaporation exceeds 2000 mm (Hao et al., 2015). The mean annual air temperature is 9.1 °C with monthly averages ranging from 23.76 °C in July to −10.08 °C in January (Feng et al., 2005). There are 135–150 frost-free days and 3100–3300 h of sunshine per year. The main physical and chemical properties of the soil layers (0–120 cm depth) are listed in Table 1. On average, the sand layer is 30 cm thick and occurs between 60 and 90 cm below the soil surface. Climatic data for the two growing seasons are provided in Fig. 1.

2.2. Experimental design and field management

This experiment used a completely randomized block design with three replicates. Each plot was 4 m wide by 12 m long with 8 plant rows. The treatments included two lateral-spacing (A1: 1.0 m, A2: 0.5 m) and two film-covering modes (M1: fully mulched, M2: partially mulched). In A1M1 and A1M2, one drip lateral was positioned at the centre of two adjacent crop rows, which were fully mulched with plastic film or partially mulched with plastic film at a width of 60 cm (Fig. 2a, b). In A2M1 and A2M2, one lateral served one row close to the crop, with full plastic film mulching or partial mulching at a width of 30 cm (Fig. 2c, d). In all treatments, the plastic film was 8-μm-thick polyethylene, and the mulched area index of M1 and M2 were 1 and 0.6, respectively. The drip irrigation systems were installed before the plastic mulch was applied and consisted of a control unit and distribution lines. The control unit consisted of a control valve, a pressure gauge and a water flow metre. Drip tape (Ø = 16 mm) with emitters spaced at 30 cm and an emitter flow rate of 1.4 l/h at an operating pressure of 0.04 MPa was used.

The total, applied irrigation of the mulched drip treatments was 60% of the average, local irrigation application in 2014 and scheduled according to evapotranspiration (E_{20} pan) (Wang et al., 2015). The irrigation amounts were 180 and 346.1 mm in 2014 and 2015, respectively. In 2015, frequent fertigation was adopted after jointing stage. In both years, the total N application rate was 300 kg N/ha for all treatments. P_2O_5 (diammonium phosphate) was spread at