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Optimizing water use efficiency and economic return of super high yield spring maize under drip irrigation and plastic mulching in arid areas of China

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A R T I C L E I N F O

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A B S T R A C T

Maize production in arid areas of Northwest China is seriously limited by water supply. Conserving irrigation water and increasing water use efficiency (WUE) are effective methods for sustainable agricultural development. The objectives of this study were to optimize irrigation water use, grain yield, WUE, and economic return of super high yield maize in a drip irrigation and plastic film mulch system in Xinjiang. Experiments were conducted in Qitia County, Xinjiang, and included four drip irrigation treatments: T1, 600 mm (CK); T2, 540 mm; T3, 480 mm; and T4, 420 mm. Six density-tolerant maize hybrids were planted in 2014 and 2015. Grain yield and economic return did not significantly change in response to a 10% decrease in irrigation level, whereas evapotranspiration decreased and WUE increased (4.61%–6.66%). High grain yield (15.7–19.1 Mg ha^{-1}), WUE (2.47–2.77 kg m^{-3}), and economic return (1691.6–2605.7 US$ ha^{-1}) were achieved under the T2 treatment. The combined techniques of drip irrigation, plastic film mulching, and increased planting density improved yield. Quadratic relationships were found between irrigation level and grain yield and between irrigation level and economic return. Irrigation level and evapotranspiration were negatively correlated with WUE. Maximum economic return and irrigation level were linearly related with the price of water. Taking into account grain yield, economic return, and ecological effects, an irrigation amount of 540 mm is optimal for drip irrigation–-plastic film mulching systems in arid areas.

1. Introduction

Irrigated agriculture is the largest single source of fresh water use, consuming about 70%–75% of the world's freshwater. Increasing global population, demand for food, livestock feed, and biofuel coupled with global climate change are putting increasing pressure on freshwater resources (Wallace, 2000; Rosegrant et al., 2009). Water scarcity is a major factor limiting crop growth and yield in arid and semiarid agricultural areas (Bozkurt et al., 2006; Hao et al., 2015). Maize (*Zea Mays* L.) is the most widely grown crop in China, maize accounting for 35.3% of total grain production in 2012. Maize is also important for livestock feed and industrial materials. However, maize production is restricted by low yield. At present, the average yield of maize is close to 6.0 Mg ha^{-1} (Li et al., 2016) in China. Therefore, achieving high maize yield is important for ensuring food security (Li and Wang, 2008, 2009; Grassini et al., 2011). To meet the projected basic human requirements in 2020, Chinese grain production will need to exceed 550 billion kg, with maize accounting for 53.1% of total grain production. It is important to increase crop yield per unit water and land, but soil, water, climate, and other factors restrict sustainable grain production. Generally, farmers tend to use excessive amounts of irrigation water to ensure maximum yield, resulting in low WUE and economic return.

In arid regions, irrigation water is the major limiting resource for agricultural yield. Water use efficiency is an important indicator for evaluating the water-saving efficiency of irrigated field crops (Kang et al., 2000; Kiziloglu et al., 2009; Deng et al., 2006; Rudnick et al., 2016; Kang et al., 2017). In a study by Liu et al. (2011), WUE was 1.60 kg m^{-3} when grain yield reached 9.5 Mg ha^{-1}. Fan et al. (2017) reported maize yield of 6.5 t ha^{-1} corresponding to WUE of 1.24 kg m^{-3}. Low WUE is a common problem throughout the world. Howell et al. (1997) reported maize WUE ranging from 1.08 to 1.62 kg m^{-3} and yield from 13 to 14 t ha^{-1}. Yazar et al. (2009)

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reported an average WUE of 1.80 kg m^{-3} and the maximum grain yield of 10.4 t ha^{-1} for maize in Turkey. In a study by Bozkurt et al. (2011), average maize grain yield varied from 1.9 to 10.4 t ha^{-1} and the maximum WUE was 1.77 kg m^{-3}. However, few studies have evaluated the economic return in response to increased WUE. Irrigation level can affect maize growth and grain yield as number of kernels per ear or kernel weight (Gavloski et al., 1992; Cakir, 2004; Payero et al., 2009; Bozkurt et al., 2011; Karasu et al., 2015). Irrigation regimes affect evapotranspiration and maize grain yield. Some studies have suggested that maize yield is a linear function of seasonal evapotranspiration (Payero et al., 2006, 2008; Kuscu et al., 2013; Kresović et al., 2016). Therefore, reducing irrigation level and improving water use efficiency are critically important to sustainable agriculture.

Water-saving irrigation measures can influence crop growth, yield, and WUE. Many techniques have been suggested for improving the yield, WUE and economic return of maize. Some scholars have discussed various water-saving irrigation technologies for reducing agricultural water use (Bassetti and Westgate, 1993; Cakir, 2004; Hassanli et al., 2009; Payero et al., 2009). Some studies have reported using straw mulching and tillage to increase soil moisture and rainfall storage (Tao et al., 2015; Cai et al., 2015). However, these approaches reduce land use efficiency and increase labor costs.

Xinjiang Province is a typical arid-semiarid region, characterized by low rainfall and high evaporation. Irrigation water shortages limit crop production, and combining drip irrigation with plastic film mulching is therefore a developing technique in this region. This method was originally developed for the production of cotton, and it was later applied to maize and other crops. As of 2012, the technique had been applied to a total area of 204.8 million ha. In Xinjiang, the maize cultivation area increased from 50.2×10^4 ha in 2002 to 86×10^4 ha in 2012. At present, drip irrigation–plastic film mulching is widely used in maize production (Fig. 1). Drip irrigation, whereby water is frequently applied to a small area near growing plants, generally results in strong crop development while limiting soil evaporation and percolation depth (Chen et al., 2015). Drip irrigation increases crop yield and WUE compared with sprinkler and furrow irrigation (Yohannes and Tadesse, 1998; Cetin and Bilgel, 2002; Ibragimov et al., 2007; Hassanli et al., 2009). Plastic mulching is also widely used for reducing soil evaporation and enhancing yield (Zhao et al., 2016; Wu et al., 2017; Fan et al., 2017). Combining mulching with drip irrigation is a new comprehensive agricultural technology that can efficiently supply irrigation water, fertilizers, and pesticides, and has been widely studied in recent years (Qin et al., 2016; Liu et al., 2017; Tian et al., 2017). Some scholars have studied the effects of drip irrigation–plastic film mulching on crop production (e.g., cotton (Du et al., 2008; Ning et al., 2015; Tian et al., 2017), and potato (Yang et al., 2017)). However, little information on grain yield, WUE, and economic return exists for high-yield (> 15 Mg ha^{-1}) maize in similar systems of China. Over recent years, the area of high-yield (> 15 Mg ha^{-1}) spring maize has increased gradually in Northwest China (Li et al., 2015a,b; Wang et al., 2012). However, the relationship between maize grain yield and irrigation level has not been clearly defined, and WUE and economic returns typically are low for drip irrigation–plastic film mulching systems. Therefore, the objectives of this study were to (i) investigate changes in maize grain yield, WUE, and economic return in a drip irrigation–-plastic film mulching system; and (ii) to explore the optimal irrigation regime for high-yield spring maize production.

2. Materials and methods

2.1. Experiment station and description

Field experiments were conducted at Qitai Farm (Qitai, Xinjiang Province, China (Fig. 2)) during the 2014 and 2015 growing seasons. The region has a temperate arid climate. Geographical and meteorological conditions are shown in Table 1. Meteorological data for the maize growing season in 2014 and 2015 were obtained from meteorological stations located near the experimental station (Table 2). The soil at the station is light loam, and its physicochemical properties were listed in Table 3.

2.2. Experimental design and field management

A split-plot design was used with maize variety as the main plot factor and irrigation level as the sub-plot factor. Surface drip irrigation and plastic film mulching techniques were adopted. Each treatment was replicated three times. The area of each plot was 48 m^2 (length: 7.27 m, width: 6.60 m). Water movement between plots was prevented by burying waterproof membranes to a depth of 1 m below the soil surface between each plot and by setting up a wide 1-m buffer zone between plots. The planting density was 12×10^4 plants ha^{-1}. Plants were seeded in alternating wide-narrow row patterns (alternating row spaces of 70 and 40 cm, respectively). Before sowing, drip tape was applied, followed by plastic film with punch holes for seedling growth. According to the hole to play the planting. A joint planter was used to synchronize these procedures (Fig. 1). To ensure uniform planting density, maize precision planters (ACME-BZQ, ACME, China) were used to manually sow the seeds to an average depth of 5.0 cm. Seeds were planted along each row and covered with thin soil. The plastic film was transparent with a width of 70 cm and a thickness of 0.01 mm (Tianye

Fig. 1. Joint planter applying drip tape, plastic film, punch holes and sowing.