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Effects of ridge-covering mulches on soil water storage and maize production under simulated rainfall in semiarid regions of China

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ABSTRACT

The ridge furrow rainwater harvesting (RFRH) system with different ridge covering materials as mulch for collecting runoff water is a valuable technique for enhancing seed filling rates and maize productivity. Therefore, a field experiments were conducted during 2 consecutive years in 2014-15, under large mobile rain-proof shelter at the Institute of Water Saving Agriculture in Semi-Arid Areas of China. Objectives of this study were enhancing soil water storage, promoting seed filling and yield of maize, with following two planting models: (i) traditional flat planting (CK); (ii) ridges covered with different mulching material (plastic film (PM), biodegradable film (BM), soil crust ridges (SC)); and two simulated rainfall levels: 320 mm and 430 mm rainfall. Results of this work revealed that mulching material on ridges had distinct effect on soil water storage in the 200 cm depth of soil at the middle of furrows and in the order of $PM_{430} \approx BM_{430} > SC_{430} > PM_{320} > BM_{320} > SC_{320}$, compared to CK_{320} and CK_{430}, respectively. The average seed yield increased by 27%, 23% and 17% for PM_{320}, BM_{320}, and SC_{320}, compared to CK_{320}, and increased by 30%, 25% and 12% for PM_{430}, BM_{430} and SC_{430} as compared to CK_{430} over 2 consecutive years, respectively. Average WUE significantly improved by ($P < 0.05$) in PM_{430} and PM_{320}, BM_{430}, BM_{320}, SC_{320}, and SC_{430} were 32.8%, 29.7%, 24.8%, 24.2%, 17.6% and 8.5% over 2 years compared to CK_{320} and CK_{430}, respectively. The effect of RFRH system on maize seed filling was significantly related to the simulated rainfall levels and the position of the seeds on the ear. Both PM_{320} and BM_{320} significantly ($P < 0.05$) promoted the seed filling rates of the superior, middle and inferior seeds. Seed-filling rates of the superior, middle and inferior seeds at the PM_{430} were also significantly increased. Our results suggested that PM_{430} and BM_{430} both significantly increased the SWS during the seed-filling process; which resulted higher grain yield and might have potential for reducing maize productivity risk under dry-land farming system.

1. Introduction

The northwest region of China accounts for less than 20% of the total water resources, but it contains 65% of the total arable land area (Li and Gong, 2002a). Furthermore, this region mainly possesses a monsoon climate, where over 70% of the rainfall occurs between June and August, which is outside the growth stage for most crops (Wu et al., 2015). Thus, water shortages and uneven rainfall distribution are the main restrictions on the development of agriculture in northwest China (Liu et al., 2015). In the semiarid region of China, the annual mean average precipitation ranges from 240 to 545 mm and it is used mainly for dryland farming. The annual evapotranspiration (ET) rate with maize is 700–880 mm, which is significantly higher than the annual precipitation, and the rainwater distribution is highly irregular and uneven. This inadequate and unpredictable rainfall often leads to water scarcity and rainwater deficiency, which is a general problem during the different growth stages for maize. Thus, low water availability can reduce production and even lead to total failure for maize crops in the semiarid area of China (Liu et al., 2002; Ren et al., 2010). Most of the precipitation in arid and semiarid regions occurs in the form of low rainfall events (<6 mm), which cannot be utilized well by maize crop, while frequent heavy rainfall occurring as thunderstorms may even lead

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to rainwater losses by surface runoff and the resulting soil erosion could affect crop production (Monneveux et al., 2006; Wang et al., 2009; Qin et al., 2014). Thus, maize production in these regions depends mainly on the erratic and irregular rainwater distribution. The average mean precipitation in the semiarid area over a 46-year period (1966–2012) was 379 mm, and thus water scarcity has constrained agricultural production. In this area, the main aim is to decrease rainwater surface runoff and enhance agricultural production by ensuring the maximum consumption of precipitation using the ridge and furrow micro-rainfall harvesting (RFRH) system (Li and Gong, 2002b).

The RFRH system comprises alternating ridges and furrows, where the ridge is usually covered with different mulching materials to facilitate micro-rainwater collection and the furrow is used for maize cultivation without mulching materials. This system has been adopted in various parts of the world (Mintesinot et al., 2004) and it is one of the most efficient methods for the efficient use of rainwater, especially light intensity precipitation, in the semiarid area of China (Deng et al., 2006). A micro-rainwater harvesting system combined with different ridge-covering mulch materials can increase the soil water availability for crops by collecting water from low intensity rainfall, thereby facilitating sustainable farming productivity and high water use efficiency (WUE) in semiarid areas of the world (Li et al., 2001). The RFRH system also reduces soil evaporation and enhances rainwater penetration (Xie et al., 2005). Moreover, Wang et al. (2004) demonstrated that RFRH with different ridge-covering mulch materials can increase the WUE and biomass for maize, as well as reducing costs for the farmer.

Using RFRH to collect surface runoff water from ridges can lead to deep infiltration into the furrows (Ali and Theib, 2004). Ren et al. (2008) simulated various precipitation levels, i.e., 440, 340, and 230 mm, and showed that RFRH could enhance the maize yield by 82.8%, 43.4%, and 11.2%, respectively, compared with flat planting cultivation, while the WUE improved by 77.4%, 43.1%, and 9.5%. The RFRH technique can improve rainwater penetration and water storage in the soil by using different mulching materials. However, plastic film mulching causes environmental problems when applied to the soil and it is not beneficial for crop cultivation, growth, and development. At present, no alternative technique can resolve this problem, although some studies have suggested that the application of biodegradable mulch and soil crust ridges in the RFRH system could be a practical solution.

The potential yield of maize can be determined based on three main components: seed weight, seeds ear^{-1}, and ears plant^{-1}. The seed weight is determined during seed filling, which is the final maize growth stage where the fertilized ovaries combine into caryopses (Yang et al., 2006). However, improving the seed filling stage is more challenging than ever in current crop farming systems (Zahedi and Jenner, 2003). Thus, it is important to determine how RFRH with different ridge-covering materials affects the grain-filling process under simulated rainfall conditions. Previous studies have shown that the seed filling characteristics differ greatly among seeds located in different positions in the ear under drought conditions, where the more inferior maize seeds are more susceptible to drought compared with the superior and middle seeds in the ear (Liu et al., 2013). Furthermore, the simulated rainfall technique has not been employed widely in the semiarid region of northwest China. Therefore, in this field study, we combined simulated rainfall with the RFRH system to determine a suitable simulated rainfall amount for enhancing crop productivity. The aims of the present study were to determine the effects of using the RFRH system with different ridge-covering materials on the soil water storage (SWS), seed-filling process, WUE, and maize yield under simulated precipitation conditions.

2. Materials and methods

2.1. Study site description

The field experiments were conducted during crop seasons (2014-15) at the Institute of Water Saving Agriculture in Semi-Arid Regions of China in Northwest A&F University, Yangling, Shaanxi Province. The site is located with latitude of 34°20′N, longitude of 108°24′E, and an elevation of 466.7 m above sea level. The climatic conditions of experimental site were semi-arid, warm temperate with annual mean air temperature 12.9 °C, mean annual maximum and minimum air temperatures were 42 °C and −17.4 °C, respectively. The total yearly sunshine duration was 2196 h and the frost free period was 220 days. The annual mean rainfall (average value of 1966–2012) was 550 mm. The rate of occasional distribution of rainfall events below the average for the reference period of 1966–2012 were about once 4 years (320 mm < rain rainfall < 430 mm) and 4 years (rainfall ≥ 430 mm), respectively during maize growing season. The rainfall amount during the months of April–October in 2014 was 313 mm and in 2015 was 330 mm. Mean soil bulk density of field was 1.37 g cm^{-3}, total nitrogen (N) 0.7 g kg^{-1}, total phosphorus (P) 0.6 g kg^{-1}, total potassium (K) 7.9 g kg^{-1}, available (N) 41.3 mg kg^{-1}, available (P) 8.56 mg kg^{-1}, and available (K) 100 mg kg^{-1}, respectively. The average field water holding capacity (FWHC) and permanent wilting point (PWP) of the root zone soil profile were 23.2% and 7.2%, respectively. The organic matter content (OM) of 0–20 cm top soil was 10.39 g kg^{-1} with pH of 7.73. The soil was a Calcic Cambisol (sand 14%, silt 26%, and clay 60%) with low fertility.

2.2. Experimental design, treatments and field management

The field experiments were carried out in large-scale water proof sheds. The internal shed dimensions were 32 m (length) × 15 m (width) × 3 m (height). The sheds were covered with transparent plastic roof. The mobile water proof sheds were used to control natural rainfall. The experiment was a 4 × 2 (ridge-furrow micro-rainwater harvesting system of 3 different ridges covering mulch materials, CK: traditional flat planting and two levels of simulated rainfall) factorial experimental design with eight treatment combinations which were coded as PM_{320}, BM_{320}, SC_{320}, CK_{320} PM_{430}, BM_{430}, SC_{430} and CK_{430}. Two levels of simulated rainfall applications, consisting of 320 and 430 mm, were applied during different maize growth stages. RFRHS were arranged by shaping the soil surface into alternate ridges and furrows. Ridge to ridge distance was 60 cm with 25 cm height and covered with plastic film mulch (PM) having a thickness of 0.08 mm; biodegradable film mulch (BM); soil crust ridges (SC) and traditional flat planting (CK). A double row of maize was sowed in furrows (Fig. 2). Each of the treatment had three plots as repeats in a completely randomized design (CRD). The length and width of each cemented pond plot was 5 m × 4.42 m with 3 m depth. Each plot was separated by 17 cm thick concrete walls to prevent inter exchange of soil moisture content. The clods on the ridges were broken into pieces. The plastic film and the biodegradable film mulch were covered on the ridge surface with the edges buried in 3–5 cm deep soil. The SC (soil crust ridges) was compacted manually with wooden blocks from 25 to 27 May 2014. The furrows were leveled as the sowing belts. The arrangement of ridges and furrows were maintained after maize harvesting in 2014, and continued to be used in the successive growing seasons. The method of covering the ridges of PM and BM was repeated from 23 to 24 May 2015. But SC remained without being destroyed.

Maize genotype, (Zhengdan 958) was planted at a rate of 75,000 plants ha^{-1} seeds were sown on June 2 for the 2014 planting year and June 4 for 2015 with a row spacing of 60 cm × 20 cm with