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Effects of ridge and furrow rainwater harvesting system combined with irrigation on improving water use efficiency of maize (*Zea mays* L.) in semi-humid area of China

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ABSTRACT

The ridge and furrow rainfall harvesting (RFRH) system collecting runoff by the plastic mulched ridges is a useful method to improve crop productivity in northwest China. We performed a field study where the RFRH system was combined with irrigation (RI) to reduce water irrigation use and to increase the crop water use efficiency (WUE) in a semi-humid climate. The amount of irrigation using RI was reduced by half compared with traditional furrow irrigation (FI) and border irrigation (BI) due to its rainwater harvesting effects. Our results showed that the RI treatment effectively alleviated drought stress during key periods of crop growth. At the jointing stage, the soil water storage in the 0–200 cm soil layer was increased by 2.82–8.02% and 2.25–8.40% compared with FI and BI, respectively, and the soil water consumption by maize below 60 cm was significantly decreased at the tasselling stage. With RI, the harvest biomass, grain yield, and WUE were significantly increased by 14.59–19.93%, 5.33–7.01%, and 12.21–18.01% compared with FI, respectively, and compared with BI, these values were significantly increased by 24.48–27.25%, 8.83–11.23%, and 14.99–22.91%, respectively. The irrigation amount was reduced by 1500 $m^3\ hm^{-2}$, and the irrigation WUE with RI was 2.1 and 2.2 times higher than that using FI and BI. The irrigation water productivity was improved by 1.71 and 5.70 times compared with FI and BI, respectively in 2011. These results suggest that combining the RFRH system with irrigation is suitable for reducing irrigation water use by enhancing the efficient utilization of local rainfall, which could have very important applications in irrigated fields in semi-humid or semi-arid areas.

1. Introduction

In China, the northern regions account for less than 20% of the total water resources, but 65% of the total arable land area (Deng et al., 2006). Furthermore, these regions are strongly governed by the monsoon climate, where over 70% of the rainfall is received between June and August, which often occurs outside the growth stage for crops (Li et al., 2000; Chen et al., 2012). Thus, water shortages and uneven rainfall distribution are the main restrictions on the development of agriculture in northern China (Dang et al., 2006). Therefore, the development of methods to improve agricultural productivity and water use efficiency (WUE) with limited water resources is an urgent requirement.

Frequent droughts mean that agricultural rainwater harvesting has received increasing attention in recent years. Agricultural rainwater harvesting collects and stores the surface runoff or rainfall in the root zone, and this has been shown to a useful method for improving crop productivity in arid and semi-arid areas (Boers et al., 1986). In particular, the ridge and furrow rainwater harvesting (RFRH) system has been popularized in northwest China since the 1980s. The major advantages of the RFRH system are increased soil water availability and crop yields by doubling the rainwater collected in plant furrows using plastic-mulched ridges (Tian et al., 2003; Li et al., 2007). Many studies have evaluated the

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impacts of the RFRH system on dry land farming. For example, Li et al. (2000) indicated that the rainwater collection efficiency of the RFRH system was 87% and it allowed the better utilization of light rain (<5 mm). Ren et al. (2008) found that when maize was grown with the RFRH system, the soil water increased by 5–12% in the 0–100 cm soil layer, the soil temperature increased by 0.7–1 °C in the 0–10 cm layer, and seed emergence was advanced by 1–2 days compared to flat planting. Wang et al. (2008) showed that the yield and WUE with potatoes were increased by 159–175% and 1.5–1.6 times, respectively. Therefore, these advantages may encourage farmers to adopt the RFRH system to cope with drought in high production farming.

Agriculture is often inefficient due to a low WUE with irrigation, which is calculated as the ratio of the irrigation water used by the crop relative to the amount of water actually applied during irrigation (Patanè et al., 2011). About 20% of the world's croplands are irrigated but they produce 40% of the global harvest, whereas 80% of the food is produced on irrigated farmland in China, thus it has an important role in feeding the population of 1.3 billion (Du et al., 2010). With the development of the economy and the increased demand for grain, the competition for water use by industry, domestic applications, ecology, and agriculture has become a serious issue (Wang et al., 2004). However, increasing the volume of irrigation or expanding the areas of irrigated farmland to obtain more food are not feasible options in northern China. Thus, the main target for increasing the crop yield with less water is the development of water-saving agriculture.

The technology of water saving mainly turns to water delivery approach, irrigation method and irrigation scheduling. And many researchers have been focused on irrigation method and irrigation scheduling for a long time. Nowadays, surface irrigation, sprinkle irrigation and micro-irrigation (e.g. drip irrigation) are the most popular irrigation methods in China. The sprinkle irrigation and drip irrigation have an advantage on water-saving benefits, which can reduce water use by 30–80% compared to surface irrigation (Albaji et al., 2010). However, for the limitation of soil texture, water quality and high cost, the sprinkle irrigation and drip irrigation are more suitable for economic crops rather than field crops in economically backward regions, especially. In this case, surface irrigation including furrow irrigation and border irrigation accounts about 97% in China due to its simple application and low energy consumption, although the irrigation efficiency is not satisfied (Deng et al., 2006). Irrigation scheduling means determining reasonable irrigation amount and optimizing water allocation for the crop. And the limited irrigation (or deficit irrigation) has been greatly advocated in recent years. High level of irrigation leads to the high evapotranspiration and biomass, but it does not produce the highest grain yield and decrease the water use efficiency relatively (Kang et al., 2002). Geerts et al. (2008) found that quinoa yields can be stabilized at 1.2 up to 2 Mg ha^{-1} with the help of deficiency irrigation by applying only half of the irrigation water required for full irrigation. Irrigation period has an important impact on biomass of maize, it is critical to time irrigations to minimize crop stress during R3 (milk) and R4 (dough) growth stages (Payero et al., 2009). Zhang and Oweis (1999) indicated that when rainfall is <300 mm, two to four irrigations and total 108–250 mm water are needed, and irrigation might be applied at elongation, booting, flowering and/or filling stages of wheat. When rainfall is above 400 mm, only one or even no irrigation is needed, if the irrigation is applied, the best time is at filling stage. Although many achievements have been made on water-saving process, little information is available on reducing irrigation by fully exploiting the available rainfall, and by using RFRH system in particular.

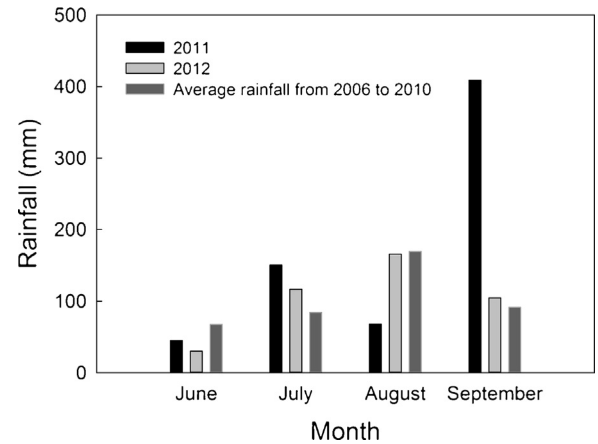

Fig. 1. Monthly rainfall distribution during the maize-growing seasons in 2011 and 2012 at the experimental site.

In the present study, we aimed to reduce the volume of irrigation water and to improve the WUE by combining the RFRH system with irrigation (RI). With RI, the RFRH system which developed in dry land was applied to irrigated farmland, and its utilization was extended from semi-arid region to semi-humid region to cope with water scarcity. We investigated the effects of the RI treatment on plant development, soil water variations, the yield of maize, and WUE when using half the amount of irrigation compared with traditional furrow irrigation (FI) and border irrigation (BI). We expect that this practice could support a complete rainwater harvesting system and allow the efficient utilization of rainfall as well as irrigation in irrigated fields in semi-humid or semi-arid areas.

2. Materials and methods

2.1. Site description

The experiment was conducted in 2011 and 2012 at the Institute of Water-saving Agriculture in Arid Areas (IWSA), Shaanxi Province, China (34°20′N, 108°04′E; 466.7 m above sea level). The annual mean temperature was 13.5 °C in the last 20 years, the total yearly sunshine duration was 2196 h, the annual mean pan evaporation was 993.2 mm, and the annual mean precipitation was 550 mm. The soil type was Lou soil (loamy clay) with a mean bulk density of 1.35 g cm^{-3} and the organic matter content, available N, P, and K in 0–40 cm soil layer were 13.27 g kg^{-1}, 38.43 mg kg^{-1}, 6.95 mg kg^{-1}, and 127.90 mg kg^{-1}, respectively. And the soil characteristic was given in Table 1. The rainfall levels during the growth period were 636.9 mm and 429.3 mm in 2011 and 2012, respectively. The distributions of the monthly precipitation during the experimental period are shown in Fig. 1.

Table 1
Properties of the soil in 0–200 cm at Yangling.

Soil mechanical composition (%)			Soil water characteristic			
2–0.02 mm	0.02–0.002 mm	<0.002 mm	Field capacity (vol%)	Wilting moisture (vol%)	Saturation moisture (%)	Initial infiltration rate (mm min^{-1})
32.55	35.08	32.36	27.07	14.11	36.11	0.32