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Nutrient and tillage strategies to increase grain yield and water use efficiency in semi-arid areas

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ABSTRACT

Water and fertilizer are major factors that influence crop productivity in dryland farming. The ridge and furrow rainfall harvesting (RFRH) system is known to be an effective planting method for improving rainwater utilization, but suitable fertilizer application rates for foxtail millet under RFRH planting have not yet been determined. In 2014 and 2015, we examined the effects of four fertilizer application rates (F0, F1, F2, and F3) under RFRH planting (RFRHP) and traditional flat planting (TFP) on the soil water content (SWC), evapotranspiration (ET), plant growth, grain yield, and resource use efficiency for foxtail millet. We found that RFRHP improved the SWC, where the SWC exhibited a decreasing trend as the fertilizer rate increased, but generally there was no significant difference among F1, F2 and F3 under both planting patterns. Compared with TFP, RFRHP produced a slightly higher maximum leaf area and dry matter accumulation, although the differences were not significant, while total ET was reduced and there were general improvements in the harvest index, grain yield, water use efficiency (WUE), agronomic efficiency, and net economic benefit. Foxtail millet responded positively to fertilizer, and F2 was the economical fertilizer input rate, where the leaf area, dry matter accumulation, and grain yield were increased slightly with no significant difference when the fertilizer rate was increased beyond F2, while agronomic efficiency was significantly decreased. The highest economic net benefit was achieved by RFRHP combined with F2, which also obtained significantly higher grain yield, WUE and agronomic efficiency compared with TFP. Thus, we recommend the RFRH system with F2 (186:96 kg N:P ha^{-1}) for high productivity and efficient foxtail millet production in semi-arid areas.

1. Introduction

Foxtail millet (*Setaria italica* L.) is one of the most important food and forage cereal crops in arid and semi-arid areas (Wen et al., 2012). Nutrient and water deficiency are the two major factors that limit increased and stabilized agricultural production in dryland farming systems (Barbieri et al., 2012). However, many dryland studies have given more attention to water use efficiency compared to fertilizer use efficiency, which limits the land potential for crop production (Abbas et al., 2005).

In dry-land farming systems, it is difficult to improve plant growth and development due to water stress, which limits the uptake of plant nutrients (Seghatoleslami et al., 2008; Nagaz et al., 2012). In recent years, ridge and furrow rainfall harvesting (RFRH) planting technology has been widely developed and applied in semiarid agroecosystems, which significantly enhances the utilization of rainwater and improves the fertilizer use efficiency (Wang et al., 2011a, 2015; Hu et al., 2014). The RFRH planting, as a rainfall harvesting system, includes rainwater harvesting zone (ridge) and planting zone (furrow). Plastic film covers the ridges to enhance rainwater harvesting efficiency, and ridges are built in the field alternating with corresponding furrows (Wang et al., 2015). The RFRH system can enhance crop production by collecting water from light rain, and retaining surface runoff from heavy rain (Tian et al., 2003; Jia et al., 2006). In addition, RFRH planting can reduce topsoil evaporation and supply sufficient water at the critical growth stages of crops, and improve water use efficiency (WUE) (Li et al., 2005; Qin et al., 2014). The RFRH system promotes soil moisture retention by suppressing evaporation of rainwater, thereby

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increasing the soil water storage and enhancing crop water use (Li et al., 2001).

The efficient use of rainwater can significantly increase fertilizer use efficiency, maintain crop production efficiency, and facilitate sustainable dryland farming (Singh et al., 2010). The soil fertility and economic returns can be optimized in semi-arid regions by considering the precipitation patterns to improve the use of rainwater with the RFRH system, thereby enhancing the supply of soil nutrients and increasing crop yields. Ren et al. (2010) showed that RFRH planting improved maize growth and increased the availability of nutrients such as nitrogen, phosphorus, and potassium. Li et al. (2004) and Tiquia et al. (2002) also found that ridge and furrow cultivation can improve the deep soil moisture levels and avoid severe drought stress at critical crop growth stages, thus generating higher crop yields. Excessively high or low fertilizer levels are not conducive for improving crop yields, whereas the optimized supply of water and fertilizer can increase the leaf area, photosynthetic rate, dry matter accumulation, and yield formation (Teixeira et al., 2014). It is implied that water can increase the availability of nutrients, whereas nutrients can also improve crop growth and subsequently strengthen crop tolerance to drought stress (Li et al., 2009). Once a certain limit is reached, a change in the opposite direction is inevitable. It has been reported that excessive fertilization may lead to crop luxurious water consumption and the risk of nitrate nitrogen leaching, thereby reducing water and fertilizer use efficiency (Kim et al., 2008; Di Paolo and Rinaldi, 2008).

The insufficient supply of nutrients and unnecessary losses of limited rainfall lead to reduced yields in semi-arid regions. Therefore, combining the RFRH system with optimized fertilizer application levels in arid regions is gradually attracting attention (Ogola et al., 2002). Previous studies of RFRH have focused mainly on water regulation, such as irrigation, ridge-furrow ratios, appropriate precipitation and cover materials (Wu et al., 2015; Wang et al., 2015, 2011b; Ren et al., 2010). Enhancing dry-land crop productivity also involves optimizing the interaction of rainwater harvesting and fertilizer application. However, crop yield response to RFRH combined with different N:P fertilizer application rates is unknown. Thus, we investigated the combined effects of RFRH and different N:P fertilizer application rates on soil moisture, plant growth, grain yields, WUE, fertilizer use efficiency and economic returns. We expect that this practice could support a complete rainwater harvesting system and provide a reference for fertilizer application to foxtail millet planting under the RFRH system in a semiarid region of China.

2. Materials and methods

2.1. Site description

This study was performed during 2014 and 2015 at the Dryland Agricultural Experiment Station, Pengyang city, Ningxia, China. The experimental site was located at a longitude of 35°79′E and latitude of 106°45′N, at an elevation of 1800 m above sea level. The climatic conditions at the research station were typical of the Loess Plateau with hilly topography, which was characterized as a semi-arid region with a warm temperate climate and an annual mean evaporation rate of 1753 mm. The average mean annual temperature = 6.1 °C, total duration of sunshine hours = 2518.2 h yr^{-1}, frost-free period = 150 days yr^{-1}, and the average annual mean rainfall = 400 mm yr^{-1}, where over 60% of the rainfall occurred in July–September, respectively. The monthly rainfall distributions of 2014, 2015 and the 40-yearaverages (1973–2013) are shown in Fig. 1. The amounts of rainfall during two experimental millet growing seasons were 295 mm and 305 mm in 2014 and 2015, respectively, in the 2015 growing season, the rainfall was well distributed with 66.3, 74.2, 38, 46.6 and 93.1 mm in May–September, while in 2014, the levels were 19, 24.7, 30, 63.6 and 146.9 mm in the same months, respectively (Fig. 1). The soil at the experimental site was confirmed as loess soil with the top soil characterized by a pH = 8.5, mean bulk density = 1.34 g cm^{-3}, average field water holding capacity = 22.4%, and permanent wilting point = 8.3%. Selected chemical properties of the experimental site for the soil layers in the 0–20 cm depth are shown in Table 1.

2.2. Experimental design and field management

The field study was performed using a completely randomized block design with three replicates. The length and width of each plot was 5.0 m × 3.6 m, respectively, and the plots were cultivated by conventional tillage. The field experiment included two planting patterns (ridge and furrow rainfall harvesting planting, RFRHP; traditional flat planting, TFP), and four fertilizer rates (F0: no fertilizer, F1: N:P at 93:48 kg ha^{-1}, F2: N:P at 186:96 kg ha^{-1}, F3: N:P at 279:144 kg ha^{-1}), thereby yielding eight treatments, as follows: (i) RFRHP + F0; (ii) RFRHP + F1; (iii) RFRHP + F2; (iv) RFRHP + F3; (v) TFP + F0; (vi) TFP + F1; (vii) TFP + F2; and (viii) TFP + F3. The RFRHP model used ridge and furrow widths of 60 cm, a ridge height of 15 cm, and the ridges were covered with plastic film mulch. The plastic film had a thickness of 0.008 mm (Tianshui Tianbao Plastic Industry Ltd, Gansu, China) and the fertilizer comprised urea (N 46%; China Petroleum Ningxia Petrochemical Production Company) with diammonium phosphate (P_2O_5 46.0%, N 18.0%; Yunnan Three Circles Sinochem Fertilizer Co. Ltd, US-sheng). At 20 days before sowing, the entire experimental area was plowed before marking out the plots. All of the nitrogen and phosphorus were applied at the time of sowing by spreading the materials evenly over the plot and plowing into the soil layer with a spade, 10 days before sowing (across the whole plot for flat planting, and into the furrows under the RFRHP model). To reduce the impacts of different treatments, each plot was separated by a wide border measuring 60 cm. An illustration of RFRHP model is shown in Fig. 2.

Foxtail millet (Datong 29) was planted at a rate of 333,333 plants ha^{-1}. The seeds were sown on April 29 in 2014 and on April 24 in 2015 with an inter-row distance of 30 cm, the foxtail millet was harvested on September 29 in 2014 and on September 26 in 2015. Irrigation was not provided during the two years of this study and weeds were controlled manually in each growing season.

2.3. Sampling and measurements

2.3.1. Soil moisture and ET

Soil cores to the depth of 200 cm with an increment of 20 cm at sowing, seedling, jointing, heading, filling and harvesting stages in the two experimental years were sampled using a manual soil ferric auger, and the gravimetric (g g^{-1}) soil water content of the 0–200 cm profile was measured by drying the soil at 105 °C to a constant weight. The soil cores were sampled from the middle of a ridge, furrow, and the side of the furrow in the RFRHP plots, where the soil water content was calculated as the mean value of the three different positions whereas in the TFP plots, the soil cores were taken in the middle of two rows. The soil water storage was calculated using the following Eq. (1) (Wu et al., 2015):

$$SWS = \sum_{i}^{n} c_i \times \rho_i \times h_i / 10 \quad (1)$$

Where SWS is the amount of soil water storage (mm),$c_i$is the soil gravimetric water content (%), ρ_i is the soil bulk density (g cm^{-3}), and $h_i$is the soil depth (cm).