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Limited irrigation and planting densities for enhanced water productivity and economic returns under the ridge-furrow system in semi-arid regions of China

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ABSTRACT

In the semi-arid regions of China, ridge-furrow (RF) planting system is being gradually implemented, in order to improve the soil moisture status and water utilisation efficiency. This study aimed to improve the efficiency of the RF system by investigating the effects of three planting densities (L: 52,500 plants ha^{-1}; M: 75,000 plants ha^{-1}; H: 97,500 plants ha^{-1}) and four kinds of limited irrigation modes (NI: no irrigation; IV: irrigation at the vegetative stage with 11 leaves; IS: irrigation at the silking stage; and IVS: irrigation at the vegetative and silking stages). Maize (*Zea mays* L.) plants mainly consumed the top surface of (0–60 cm) soil water, whereas the deep layer (120–200 cm) of soil moisture was less affected under the RF system, and the average soil water storage of 0–60, 60–120, and 120–200 cm decreased by 58.7, 39.1, and 7.1 mm, respectively, during the entire growth period. Limited irrigation at the vegetative and silking stages had a positive effect on biomass, leaf area index, and evapotranspiration, but did not significantly increase grain yield, water use efficiency (WUE_G), irrigation WUE ($IWUE_G$), and irrigation water productivity (IWP_G). The average data obtained over two years showed that medium planting density with limited irrigation at the silking stage (M-IS) treatment significantly increased WUE_G, $IWUE_G$, and IWP_G by 5.7, 98.5, and 92.6%, respectively, compared with those in the M-IVS treatment. Economic benefit analysis also showed that M-IS treatment resulted in greater net profit (2313.3 USD ha^{-1}). Thus, the M-IS treatment could be a suitable planting model for improving maize grain yield, economic benefit, and water use in the semi-arid regions of China.

1. Introduction

In recent years, global climate change has led to frequent droughts in many areas, increased the degree of drought, and exacerbated the threat of drought to food production (Tietjen et al., 2016). Approximately 60% of arable land in China belongs to dry farming, of which 40% is located in semi-arid regions (China Agriculture Yearbook Editorial Board, 2001). The yield and water use efficiency (WUE) of maize in the region are relatively low, and the drought disaster area is approximately 40%; thus, this region is one of the most arid and poor areas in China (Liu et al., 2013a,b). Addressing the current drought problems requires the development and utilisation of rainwater resources and popularisation of water-saving irrigation techniques to improve yield and WUE (Lian et al., 2016; Wu et al., 2015). Ridge-furrow (RF) planting system is a catchment agriculture technology that involves building of ridges and furrows in the field–mulching is performed on the ridge and crops are planted in the ditches. This method ensures rainwater and soil moisture conservation and has become one of the main strategies for saving agricultural water (Li et al., 2000; Wiyo et al., 1999). The RF system can increase soil water storage (SWS)

Abbreviations: WUE, water use efficiency; RF, ridge-furrow; SWS, soil water storage; IWUE, irrigation water use efficiency; IWP, irrigation water productivity; ET, evapotranspiration; WUE_G, water use efficiency of grain yield; $IWUE_G$, irrigation water use efficiency of grain yield; IWP_G, irrigation water productivity for grain yield; WUE_B, water use efficiency of biomass; $IWUE_B$, irrigation water use efficiency of biomass yield; IWP_B, irrigation water productivity of biomass yield; LAI, leaf area index; TI, total input; TO, total output; NP, net profit; DAP, days after planting; Y, year

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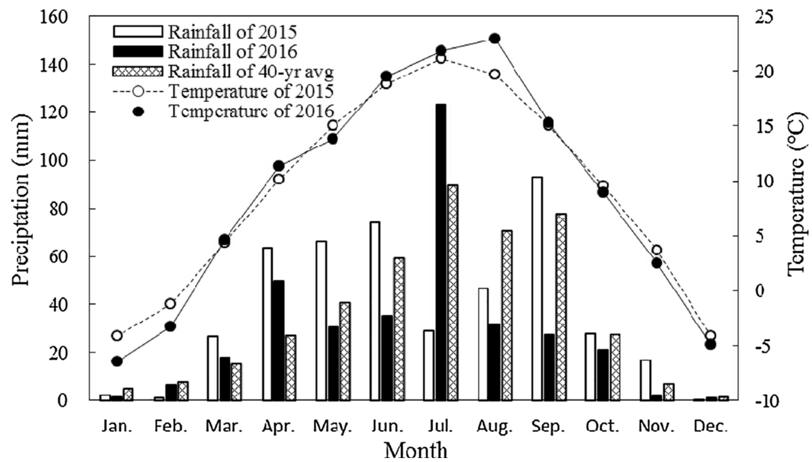

Fig. 1. Monthly rainfall distribution in 2015–16 and the 40-year average (40 a) at Pengyang Experimental Station, Ningxia Province, China.

by allowing runoff through the ridge surface and gathering it in the planting furrows, thereby creating a superimposed effect of light rain amount and promoting the infiltration of rainfall; further, mulching restrains soil evaporation and thus promotes crop growth and increases grain yield and WUE (Ren et al., 2008; Wu et al., 2015). Although many studies have successfully established water-saving farming techniques, understanding how the RF system can completely utilise the available precipitation and limit irrigation with different planting densities is still necessary.

Regulation of planting density is a key measure and simple method for increasing the yield of corn. Increasing the planting density might increase maize competition pressure and soil water demand. Further, only increasing density cannot ensure significant increase in the yield of maize; irrigation should be provided during the critical period to meet the demand of water under high planting density. Yang et al. (2004) showed that water shortage at the trumpet stage changed maize ear length, ear diameter, bald tip length, grain number per row, grain number per ear, grain weight per spike, and 100-kernel weight, resulting in lower yields; further, supplying water at the trumpet stage could improve the biomass and grain yield. However, Fan et al. (2014) found that sensitivity to moisture was in the following order: silking stage > vegetative stage > filling stage by conducting experiments in the Loess Plateau of China, and showed that soil water storage at the silking stage could decrease the maize ear length and grain number, reducing the grain yield by 9.3–18.3%. Liu et al. (2013a,b) showed that, in the rain-fed agricultural region of China, drought at the corn silking stage could significantly shorten the duration of maize grain filling and decrease grain weight, thereby reducing yield. Wang et al. (2013) found that ear length and grain number increased with increasing irrigation amount, and the 100-kernel weight first increased and then decreased with increasing irrigation amount. They indicted that proper irrigation amount can improve grain yield and irrigation WUE (IWUE), and excess water can promote biomass yield, but not the grain yield and irrigation water productivity (IWP). Maize is a high-water-consuming crop, and irrigation water is scarce in semi-arid regions of northwest China. Therefore, determining the growth stage of corn that requires small amounts of irrigation in order to achieve optimum yield, IWP, and net input is important.

Although many studies have investigated corn planting density and irrigation amount, no consensus has been reached on maize planting density, irrigation amount, and irrigation time in semi-arid regions of northwest China. Further, few studies have determined the effect of the comprehensive regulation of planting density, irrigation amount, and irrigation period on the yield and WUE under the RF system. To determine the suitable maize planting density with limited irrigation time and amount under the RF system, we established plots with different planting densities and limited irrigation modes and elucidated their effects on spring maize yield, yield components, SWS, evapotranspiration (ET), economic return, and WUE. Our findings suggest that the RF planting system combined with limited irrigation can be effectively used for the efficient usage of precipitation and irrigation water and has good applicability in semi-arid regions of China.

2. Materials and methods

2.1. Study site description

Field studies were performed in 2015 and 2016 in Pengyang City, Ningxia Province, China. The research site is located at the eastern foot of Liupan Mountain (longitude, 106°45′E; latitude, 35°79′N; elevation, 1800 m above sea level). The study area is typical of the Loess Plateau with hilly topography, which is characterized by the temperate semi-arid climate with an average annual potential evaporation of 1753 mm. The average annual temperature is 8.1 °C; average duration of sunshine, 2518 h y^{-1}; and average annual mean rainfall, 410 mm y^{-1}. The amount of rainfall during the maize growing season was 335.2 mm in 2015 and 251.6 mm in 2016. The monthly rainfall during the two maize growing seasons and the 40-year monthly averages (1977–2016) are shown in Fig. 1. The precipitation was better distributed in the 2015 growing season than in the 2016 growing season. The soil at the research site was a Calcic Cambisol (sand 14%, silt 26%, and clay 60%), with the top soil characterised by a pH of 8.5; the characteristics of the soil from 0 to 60 cm in depth at the research site are shown in Table 1.

2.2. Experimental design and field management

The experiment was performed in a completely randomised block design with three replications. In 2015–16, we conducted field research in the Loess Plateau of China to evaluate the effects of three plant densities [low (L): 52,500 plants ha^{-1}; medium (M): 75,000 plants ha^{-1}; high (H): 97,500 plants ha^{-1}] and four limited irrigation patterns

Table 1
Chemical properties of the top 0–60 cm layer of soil in the experimental fields at Pengyang Experimental Station, Ningxia Province, China in 2015 and 2016.

Soil layer (cm)	SOC (g kg^{-1})	SAN (mg kg^{-1})	SAP (mg kg^{-1})	SAK (mg kg^{-1})	STN (g kg^{-1})
0–20	9.78	61.52	11.26	168.29	1.01
20–40	7.99	43.86	7.67	119.36	0.93
40–60	7.61	40.65	5.85	100.15	0.91

Abbreviations: SOC, soil organic carbon; SAN, soil available nitrogen; SAP, soil available phosphorus; SAK, soil available potassium; STN, soil total nitrogen.