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# Strategies of supplemental irrigation and modified planting densities to improve the root growth and lodging resistance of maize (*Zea mays* L.) under the ridge-furrow rainfall harvesting system

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ABSTRACT

In the semi-arid area of northwest China, a ridge-furrow rainfall harvesting (RFRH) system and supplementary irrigation techniques have been implemented to increase crop yields. However, the effects of supplementary irrigation and planting density on maize root growth and lodging resistance under the RFRH system are unknown. Therefore, we conducted field trials implementing three planting densities (Low: 52,500 plants ha$^{-1}$; Medium: 75,000 plants ha$^{-1}$; High: 97,500 plants ha$^{-1}$) and four irrigation modes (NI: no irrigation; IV: irrigation at the 11-leaf stage; IS: irrigation at the silking stage; and IVS: irrigation at the 11-leaf and silking stages) under the RFRH system. The results showed that the average root length density (RLD) and root surface area density (RSD) in the 0–100 cm soil layers increased at the silking and dough stages under medium and high densities compared with low density. However, the root weight under high density significantly decreased compared with that under low density. Increased planting density significantly increased ear height and the ear height coefficient, leading to an increased probability of maize lodging. The root and stalk lodging rates under high density were higher than those under low and medium densities. Compared with NI treatment, at the dough stage, the average RLD and RSD increased in all irrigation treatments; supplementary irrigation also increased the root weight and root shoot ratio. The results showed that the grain yield under IS and IVS treatments significantly increased compared with that under NI treatment. The total lodging rate under IVS treatment was 41.2% higher than that under IS treatment. Therefore, the IS treatment under medium density achieved a higher grain yield (13.2 t ha$^{-1}$) and reduced maize lodging, which could be a suitable planting model in semi-arid areas.

## 1. Introduction

Increasing planting density is a simple method for obtaining a higher yield of maize (Ren et al., 2016). However, increased planting density leads to increased competition for space, which increases competition for light, moisture, and nutrients among maize plants. Increased competition among roots is particularly important because they are the main organs that absorb moisture and nutrients (Liu et al., 2012a,b; Mansfield, 2012). Increased planting density may also lead to a higher risk of lodging (Tokatlidis et al., 2010), and lodging is one of the major causes of reduced maize grain yield (Zhang et al., 2014a,b). Maize lodging and premature senescence are closely related to the growth of roots (Kamara et al., 2003; Manzur et al., 2014). Maize roots have the effect of supporting plants and fixing them in place (Tuberosa et al., 2002). Root research is one of the main areas to further improve plant productivity (Craine et al., 2003). The study of root characteristics is extremely important in optimising maize production in semi-arid areas because root development and distribution affect the crop

*Abbreviations:* RFRH, ridge-furrow rainfall harvesting system; RLD, root length density; RSD, root surface area density; RLR, root lodging rate; SLR, stalk lodging rate; TLR, total lodging rate; RSR, root shoot ratio; SDM, shoot dry matter; SD, stem diameter; PH, plant height; EH, ear height; EHC, ear height coefficient; CG, centre of gravity; RL/TL, root lodging/total lodging; IM, irrigation modes; PD, planting density

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

| Year | Jan. | Feb. | Mar. | Apr. | May. | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2015 | 2.2 | 1.2 | 26.7 | 63.5 | 66.3 | 74.2 | 29.0 | 46.6 | 93.1 | 27.9 | 16.6 | 0.4 |
| 2016 | 1.4 | 6.6 | 18.0 | 49.7 | 30.7 | 35.2 | 123.3 | 31.7 | 27.5 | 21.2 | 2.0 | 1.0 |
| 40-yr avg. | 5.0 | 8.0 | 15.5 | 27.2 | 40.8 | 59.4 | 89.6 | 70.6 | 77.8 | 27.6 | 7.2 | 1.8 |

uptake of moisture and nutrients (Fageria, 2004), which in turn affects plant growth and crop yields (Doussan et al., 2006).

Root length density (RLD) and root surface area density (RSD) are key root morphological characteristics that directly influence the function of the whole root system (Lynch, 2011). Compared with short roots, longer roots can increase the supply of nutrients to the plant, and crops with longer roots can be better adapted to semi-arid environments (Fageria, 2004). Many studies (Lynch, 1995; Liang et al., 1997; Xue et al., 2003) have shown that the distribution of roots in the soil profile has a more important effect than root dry weight on the water absorption function of roots and crop productivity, and distribution also has a high degree of plasticity. Hammer et al. (2009) found that root architecture and root uptake of water and nutrients were crucial for increasing crop yield under high-density planting. Therefore, it is necessary to study the root characteristics of corn under high planting densities and determine how to increase the density and decrease the lodging of maize.

In the semiarid Loess Plateau of northwest China, low precipitation, high evaporation, serious water loss, and soil erosion are significant environmental hazards for crop production (Li et al., 2010; Liu and Zhang, 2007). Most agricultural production is constrained by drought and poor soil fertility caused by water and wind erosion (Kang et al., 2001; Wang et al., 2016). Soil and water loss is a complex physical process involving cultivation, rainfall characteristics, and soil properties (Chen et al., 2012). The traditional tillage system cannot retain rainwater or control water loss and soil erosion during heavy rain events, resulting in poor rainfall utilization and ultimately soil degradation. Thus, economic development and agricultural productivity in this region is severely constrained (Li et al., 2015; Liu et al., 2014). The ridge-furrow rainwater harvesting (RFRH) system has been successful in reducing drought risk and controlling water loss and soil erosion in this area (Li et al., 2010; Wang et al., 2016). The RFRH system is widely used because it helps crops efficiently use water and thus increases stability in agricultural production (Li et al., 2016; Zhang et al., 2014a,b). This system is a catchment agriculture technology that involves building ridges and furrows in the field, with mulching performed on the ridge and crops planted in the furrows. The root is well developed in the RFRH system, because of the loose soil and good ventilation under the ridges (Chassot and Richner, 2002). Many studies have shown that the RFRH system can promote the growth and development of maize by significantly increasing plant height, dry matter, and grain yield, compared with conventional tillage (Liu et al., 2014; Mo et al., 2017; Zhang et al., 2017). The RFRH system has become one of the main tillage measures to improve maize yield in arid and semi-arid regions of northwest China (Wang et al., 2016; Wu et al., 2015). However, further study is needed to determine how to combine the advantages of RFRH with supplementary irrigation and establish the appropriate planting density of maize.

In the present study, we examined the effects of planting density and supplementary irrigation on maize plant height, stem diameter, ear height, centre of gravity, dry matter, root characteristics, lodging rate, and grain yield under the RFRH system. The aim was to ascertain the optimal period and amount of irrigation and determine an optimal planting density for maize under the RFRH system in semi-arid regions.

## 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 climatic conditions of the study area are typical of the Loess Plateau with hilly topography, which is characterised by a temperate semi-arid climate with an average annual free water evaporation was about 1700 mm. The annual mean temperature is 8.1 °C; total duration of sunshine hours is 2518 h $y^{-1}$. The monthly rainfall during the two maize growing seasons and the 40-year monthly averages (1977–2016) are shown in Table 1. The 40-year annual precipitation was 430.5 mm, while the 40-year average precipitation during the maize growing seasons (from April 20 to September 30) was 340.2 mm. The annual precipitation was 447.7 mm in 2015 and 348.3 mm in 2016, while precipitation during the maize growing season was 335.2 and 251.6 mm, respectively. The monthly precipitation in April, May, June, August, and September was higher in 2015 than in 2016. The rainfall was 123.3 mm in July 2016 and was mainly concentrated from July 3–11 (113.2 mm). Although this rainfall was higher than the 40-year mean for July (89.6 mm), 2016 was a dry year compared with the 40-year mean annual record. In both years, the precipitation in August was less than the 40-year average. However, the rainfall in April, May, June, and September 2015 was higher than the 40-year average. During the maize growing season, 2015 experienced normal precipitation when compared with the 40-year average. The precipitation was better distributed in the 2015 growing season than in the 2016 growing season. According to the FAO/UNESCO Soil Classification (FAO/UNESCO, 1993), the soil at the research site is Calcic Cambisol. The soil characteristics of the 0–20 cm soil layer in 2015 were as follows: soil organic carbon, 9.78 g $kg^{-1}$; total nitrogen, 1.01 g $kg^{-1}$; available N, 61.52 mg $kg^{-1}$; available phosphorus, 11.26 mg $kg^{-1}$; available potassium, 168.29 mg $kg^{-1}$; and with a pH of 8.5.

### 2.2. Experimental design and field management

In 2015–16, we conducted field research in a semi-arid region 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 supplementary irrigation patterns [NI: no irrigation; IV: irrigation (375 $m^3$ $ha^{-1}$) at the 11-leaf (V11) stage; IS: irrigation (375 $m^3$ $ha^{-1}$) at the silking stage; and IVS: irrigation (750 $m^3$ $ha^{-1}$) at the 11-leaf and silking stages] under the RFRH system. The experiment was performed in a completely randomised block design with three replications. The length and width of each plot was 12.0 m and 4.8 m (area = 57.6 $m^2$), and a 1.2 m wide isolation belt was placed between each plot to prevent water leakage. In the RFRH system (Fig. 1), the ridges were 60 cm wide and 15 cm high and covered with plastic film; the furrows planted with seedlings were 60 cm wide. The following seeding spacing was used: L (31.8 cm), M (22.2 cm), and H (17.1 cm). Maize (Dafeng 30) was sown on 23 April 2015 and 21 April 2016 using a hole-sowing machine with a seeding depth of 4–5 cm. The fertilizer application was the same in all treatments, and base fertilizer containing 150 kg $ha^{-1}$ N and 150 kg $ha^{-1}$ $P_2O_5$ was spread evenly over the furrow and ploughed into the soil layer. Top