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Effects of planting patterns and sowing densities on grain-filling, radiation use efficiency and yield of maize (*Zea mays* L.) in semi-arid regions

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ABSTRACT

The ridge-furrow rainwater harvesting system is a valuable technique for collecting runoff water and increasing radiation use efficiency to improve crop production. Field experiments were conducted over two consecutive years (2015–16) on a loess soil in semi-arid regions of China. Three different planting densities (L: 52500 plant ha^{-1}; M: 75000 plant ha^{-1}; H: 97500 plant ha^{-1}) and three different planting patterns (RF: ridge and furrow rainfall harvesting system; FM: flat planting with plastic film mulching; CP: conventional planting without plastic film) were used to measure various maize characteristics. The objectives were to enhance the water use efficiency (WUE), radiation use efficiency (RUE), and promote the grain-filling process and yields of maize. The results showed that under the same densities, there was no significant differences between the average filling rate (G_{mean}) and the maximum filling rate (G_{max}) ($P > 0.05$) during the normal-precipitation year (2015). However, the G_{mean} and G_{max} in the RF and FM treatments were significantly higher than the CP treatment in dry year (2016). Under the same densities, the number of grains per row, number of kernels per ear, and kernel yield per plant of RF and FM treatments were significantly higher than those of the CP treatment. These maize yield components decreased with increased planting densities under the same planting patterns. Compared to the CP treatment, the average annual grain yield under the RF and FM treatments increased by 33.4% and 30.0%, respectively. Compared to the CP treatment, the average annual RUE in the RF and FM treatments increased by 12.4% and 11.5% before silking and increased 17.7% and 14.7% after silking, respectively. Under the RF system with a middle planting density (M-RF) promoted grain-filling rate, grain yield, yield components, WUE, and RUE. Therefore, we concluded that M-RF model is the most suitable for increases maize yield and RUE in the semi-arid regions of China.

1. Introduction

Planting density is one of the most important factors that affect grain yield of maize, being possible to increase maize yield, water use efficiency (WUE) and average grain-filling rate (Feng et al., 2014). It has been shown that varying the maize planting density greatly affects the grain-filling process, yield and yield components (Sangoi et al., 2002). As planting density increases the number of spikes per unit area increases while the number of grains per ear and 100-kernel weight decreases (Borrás et al., 2003; Echarte et al., 2000). Similarly, the maximum and average maize grain-filling rate has been shown to significantly decrease with increasing planting density (Zhang et al., 2015).

Plant photosynthesis and biomass are closely related to photosynthetically active radiation (IPAR) canopy interception (Sauer et al., 2007). Reasonable maize planting density is the basis for creating a successful population structure that encompasses desirable leaf area index and makes full use of light energy for improved leaf photosynthetic capacity (Yang et al., 2010; Wajid, 2004). Numerous studies have shown that photosynthetically active radiation

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(IPAR) interception increases with increasing maize planting density (Shen et al., 1993; Yang et al., 2010). However, if the planting density is too great it will reduce the ability of light to penetrate the lower canopy (Liu et al., 2014), resulting in premature senescence of the lower leaves (Borrás et al., 2003) and reducing the radiation utilization efficiency (RUE) (Lin et al., 2016). Ultimately, this significantly reduces yield and yield components of maize crop (Borrás et al., 2003; Sangoi et al., 2002; Maddonni and Otegui, 2004). Conversely, the use of high density populations induces undesirable phenotypes such as apical dominance, barrenness and decreased numbers of ears per plant and kernels set per ear (Sangoi et al., 2000).

The optimum sowing density for obtaining the highest maize yield in different regions was different. A study on maize crops in the eastern part of the American Corn Belt proposed a suitable planting density of 98,800–104,500 plants ha^{-1} to have a positive effect on yield and yield components (Stanger and Lauer, 2006). Studies based in semi-arid regions recommend planting densities between 67,000–70000 plants ha^{-1} to achieve maximum corn yield (Lamm et al., 2008; Alkaisi and Yin, 2003). Another study suggests that maize planting densities at 90,000 plants ha^{-1} get the highest grain yield in semi-arid regions of china (Huang et al., 2012). Although there is extensive research on maize planting density, there is no single recommendation encompassing all environmental conditions. Optimum density varies depending on climatic factors as well as soil fertility, hybrid selection, planting date, planting pattern and harvest time (Sangoi et al., 2002; Kucharik, 2008; Burken et al., 2013).

More than 60% of China's cultivated land is located in arid and semi-arid areas (China Agriculture Yearbook Editorial Board, 2001). These areas lack underground water and have minimal precipitation. Arid and semi-arid environment soils are not conducive to effective water absorption and continuous water shortages and seasonal drought seriously restrict maize yields (Gan et al., 2009; Turner, 2004). Studies show that film mulching has obvious effects on corn yield such as improved soil environments, reduced soil evapotranspiration and significantly increased maize yields compared to bare land cultivation (Wang et al., 2012; Gao et al., 2014). In recent years, the ridge-furrow rainwater harvesting (RF) system has been applied in arid and semi-arid regions of the world in the form of plastic film mulch (Gan et al., 2013; Li et al., 2013). The RF system can conserve more rainwater; extend the period of water accessibility, and efficient to optimize crop productivity (Chakraborty et al., 2008; Zhou et al., 2009). The RF system also significantly increases the utilization of rainwater by accumulated water from light precipitation and preserving surface runoff from heavy rainfall, and reduces soil temperature and evapotranspiration rate (Hu et al., 2014). Compared to conventional flat cultivation, the ridge-furrow rainwater harvesting system can drastically improve soil moisture conditions (Ren et al., 2010; Li et al., 2004) and avoid crop drought stress at critical growth stages, thus significantly promoting maize growth, increased WUE and yield (Wang et al., 2015b; Hu et al., 2014). When soil moisture is inadequate during the maize grain-filling stage, grain-filling rates decrease and plant leaves prematurely senescence, resulting in grain yield reduction (Sayed and Gadallah, 1983; Wang et al., 2014). RF systems have a higher water holding capacity, improving soil moisture and thermal status and positively affecting average grain-filling rates and accelerating the grain-filling process (Gao et al., 2015). It is important to note that many studies show that crop yield is positively correlated with RUE and that drought stress in maize crops reduces the intercepted photosynthetically active radiation accumulation (IPAR) and RUE (Earl and Davis, 2003; Torres et al., 2016; Morales-Ruiz et al., 2016).

There is little research regarding the coupling of rainwater harvesting techniques and varying planting densities effect on the grain-filling rate and RUE in semi-arid zones. In the present study, there were studied the effects of three different planting patterns and three sowing densities on grain-filling characteristics, radiation utilization efficiency, WUE, yield and yield components of spring maize were measured. The purpose of this study is to determine the appropriate planting density and plastic film mulching method and improving the efficiency of water and solar radiation utilization in an arid farming system.

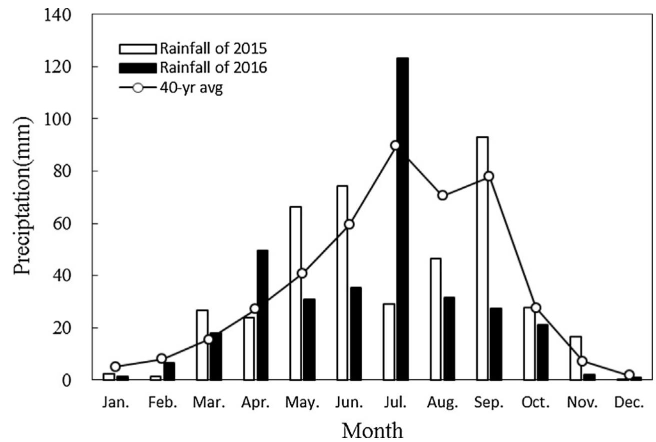

Fig. 1. Monthly rainfall distribution in 2015-16 and the 40-year average at the Pengyang Experimental Station, Ningxia Province, China.

2. Materials and methods

2.1. Climate and soil

Field studies was performed in 2015 and 2016 at the Dry-Lland Agricultural Experimental Station, Pengyang City and Ningxia Province, China. The experimental site was located at latitude 35°79′N and latitude 106°45′E at an elevation of 1800 m above sea level. The Loess Plateau in the area of the research station has hilly topography and is a semi-arid region with a warm temperate climate. The average annual temperature was 8.1 °C and the average hours of sunshine are 2518 h yr^{-1}. There is a frost-free period of approximately 140–160 days yr^{-1} and an average annual mean rainfall of 410 mm yr^{-1}, with over 60% of the rainfall occurring from July to September. The average annual free water evaporation was 1753 mm. The amount of rainfall during the maize growing season was 335.2 mm in 2015 and 251.6 mm in 2016. The monthly amounts of rainfall during the two maize growing seasons and the 40-year monthly averages (1977–2016) are shown in Fig. 1. The soil in the research site is a Calcic Cambisol (sand 14%, silt 26%, and clay 60%), pH 8.5, with a mean bulk density of 1.34 g cm^{-3}. The soil characteristics from 0 to 40 cm deep at the research site is shown in Table 1.

2.2. Experimental design

This study was performed with a randomized complete block design with three replications. The length and width of each plot were 12.0 m and 4.8 m, respectively (area = 57.6 m^2). A 1.2-m-wide isolation belt and a ridge were placed between each plot to prevent water leakage. There were evaluated the effects of three sowing densities (L: 52,500 plants ha^{-1}; M: 75,000 plants ha^{-1}; H: 97,500 plants ha^{-1}) and three different planting patterns (RF: ridge and furrow rainfall harvesting system; FM: flat planting with plastic film mulching; CP: conventional flat planting). In the RF system, the ridges and furrows were 60 cm wide and 15 cm high, and they were covered with plastic film 0.9 m wide and 0.008 mm thick. Traditional flat planting and plastic film-covered furrows of 70 cm