Agricultural Water Management 202 (2018) 19–32

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Effect of planting density and pattern on maize yield and rainwater use efficiency in the Loess Plateau in China

Qianmin Jia[a,b,c], Lefeng Sun[a,b,d], Shahzad Ali[a,b,d], Yan Zhang[a,b,d], Donghua Liu[a,b,d], Muhammad Kamran[a,b,d], Peng Zhang[a,b,d], Zhikuan Jia[a,b,d,*], Xiaolong Ren[a,b,d,*]

[a] Institute of Water Saving Agriculture in Arid Areas of China, Northwest A&F University, Yangling, Shaanxi, 712100, China
[b] Key Laboratory of Crop Physi-Ecology and Tillage Science in North-Western Loess Plateau, Ministry of Agriculture, Northwest A&F University, Yangling, Shaanxi, 712100, China
[c] College of Forestry, Northwest A&F University, Yangling, Shaanxi, 712100, China
[d] College of Agronomy, Northwest A&F University, Yangling, Shaanxi, 712100, China

ARTICLE INFO

Keywords:
Plastic film mulching
Soil temperature
Soil water
Maize growth
Evapotranspiration
Water use efficiency

ABSTRACT

We conducted a two-year field research to evaluate the effect of three planting densities (L: 52,500, M: 75,000 and H: 97,500 plants ha^{-1}) and three different planting patterns (RF: ridge with plastic film mulching; FM: flat planting with plastic film mulching; and CP: conventional planting without mulching) on maize yield. Results showed that, at each planting density, average topsoil temperature (5–25 cm) was improved under FM and RF, relative to CP, before silking. This resulted in earlier emergence and accelerated plant development. Compared to CP, RF significantly increased soil water storage (SWS) at the end of the fallow season and provided non-limiting water conditions for early seedling growth. During the growing season, when rainfall was more abundant, RF prevented evapotranspiration (ET); thereby, favouring SWS. Furthermore, when rainfall was scarce, RF provided the crop with additional soil moisture, which resulted in increased ET. Under RF and FM, the two-year average grain yield increased by 33.4% and 30%, respectively; while, water use efficiency (WUE) increased by 34.2% and 27.5%, respectively; similarly, rainwater use efficiency (RUE) increased by 35.6% and 32.1%, respectively. In a normal year (2015), grain yield, WUE and RUE, significantly increased as planting density increased from low to moderate; but not in a dry year (2016). Under such conditions, no significant differences were observed in grain yield, WUE or RUE among planting density treatments within the same planting pattern. Under moderate planting density, the two-year average final aboveground dry matter, grain yield, WUE and RUE in RF increased by 14.7%, 31.8%, 31.9% and 34.1%, respectively, compared to CP. Therefore, we conclude that RF is the most suitable planting pattern under moderate planting density for increasing maize yield in the Loess Plateau in China.

1. Introduction

Scarce precipitation and low water availability are the main factors limiting plant growth, development and yield in arid and semi-arid areas (Amanullah and Adil, 2015; Gan et al., 2009). Approximately 60% of all cultivated land in China is dryland and approximately 40% of dryland farming is carried out in the region of the Loess Plateau (Editorial Board of China Agricultural Yearbook, 2001). Water shortage is the primary factor limiting agricultural productivity and economic development in such areas (Li et al., 2004a; Liu and Zhang, 2007). In the Loess Plateau of northwest China, there is no more water available for crop irrigation; thus, rainfall is the major water resource for agricultural productivity (Li et al., 2004b). However, rainfall is limited and high evaporation often limits crop yields in this area (Li et al., 2013a,b). Therefore, it is essential to efficiently exploit rainwater resources to maximize crop yield and rainwater use efficiency (RUE), which requires both, better methods of capturing rainfall and reducing evaporation.

Some technologies have recently been developed to enhance crop yield and RUE in semi-arid regions of China (Turner et al., 2011), including, mulching with plastic film (Zhou et al., 2009), rainwater harvesting (Yuan et al., 2003), ridge-furrow mulching (Ren et al., 2016), and crop residue retention (Kong, 2014). Among these agronomic measures, mulching with plastic film is becoming a widely used technique in semi-arid areas and has recently been widely adopted in the northwest Loess Plateau (Li et al., 2004b; Liu et al., 2014a, 2014b). Various studies have shown that plastic film mulching significantly

* Corresponding authors at: Institute of Water Saving Agriculture in Arid Areas of China, Northwest A&F University, Yangling, Shaanxi, 712100, China
E-mail addresses: jiazhk@126.com (Z. Jia), rxlcxl@aliyun.com (X. Ren).

https://doi.org/10.1016/j.agwat.2018.02.011
Received 3 June 2017; Received in revised form 2 February 2018; Accepted 10 February 2018
0378-3774/

improved soil moisture conservation (Zhou et al., 2009), increased topsoil temperature (Wang et al., 2015), reduced evaporation (Liu et al., 2014a, 2014b), suppressed weed growth (Hegazi and Ogier, 2000) and improved crop yield (Liu and Siddique, 2015). The ridge-furrow rainfall harvesting (RF) system is a new film mulching cultivation technology, which includes a rainwater harvesting zone (ridge) and a planting zone (furrow) (Gan et al., 2013). In the RF system, the mulched ridges serve as a runoff surface that allows rainwater to be channelled to the furrows, where rain can penetrate into the soil (Liu et al., 2014a, 2014b). In addition, RF planting can reduce topsoil evaporation and increase soil water storage, thereby, supplying sufficient water at critical crop growth stages to increase WUE (Qin et al., 2014).

Increasing planting density is a key practice used worldwide to increase maize yield, and it is a simple and effective method for increasing yield in semi-arid regions as well (Tokatlidis et al., 2011; Turgut et al., 2005). Griesh and Yakout (2001) suggested that a planting density of 50,000 to 56,000 plants ha^{-1} is optimal, because it reduced intraspecific competition; thereby, increasing yield. However, Ryan et al. (2011) reported that a planting density of 81,700 to 107,900 plants ha^{-1} resulted in the highest yield (12,500 kg ha^{-1}). Li et al. (2013b) showed that over a certain range of planting densities, leaf area index (LAI) and grain yield increased with increasing planting density. However, if planting density is too high, leaf shading causes poor ventilation and light penetration, resulting in thin stems, increased maize lodging and decreased dry matter, which ultimately lead to lower grain yield (Farnham, 2001; Nyakudya and Stroosnijder, 2014; Trachsel et al., 2016). Although many researchers have studied maize planting density, research on the appropriate density of spring maize under the RF system has not been reported. To improve maize yield and RUE in the Loess Plateau of China, it is important to determine the most suitable planting densities for spring maize under the RF and plastic film mulching cultivation systems. Therefore, we tested different planting patterns under three planting densities. The objectives of our study were (1) to determine the appropriate planting density and planting patterns for spring maize and (2) to investigate the efficiency of planting patterns utilizing different planting densities, in terms of grain yield, WUE, RUE, evapotranspiration and soil water storage.

2. Materials and methods

2.1. Study site description

This research was 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; the area consists of hilly topography and is characterized by a temperate semi-arid climate. The annual mean temperature is 8.1 °C, the annual mean duration of sunshine is 2518 h y^{-1}, the annual mean rainfall is 410 mm y^{-1}, and the annual mean potential evaporation is 1753 mm. The amount of rainfall during the maize growing season was 335.2 mm in 2015 (a normal year) and 251.6 mm in 2016 (a dry year). The monthly amounts of rainfall and air temperature during the maize fallow and growing seasons in both years as well as the 40-year monthly mean rainfall (1977–2016) are shown in Fig. 1. According to the FAO/UNESCO soil classification system (FAO/UNESCO, 1993), the soil at the research site was a Calcic Cambisol (14% sand, 26% silt, and 60% clay); the topsoil had a pH of 8.5 and a mean bulk density of 1.34 g cm^{-3}. The characteristics of the soil at a depth of 0–60 cm at the research site are shown in Table 1.

2.2. Experimental design and field management

The experiment consisted of a completely randomized block design with three replications. In 2015–16, we conducted field research on the Loess Plateau of China to evaluated 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 three different planting patterns (RF: ridge with plastic film mulching; FM: flat planting with plastic film mulching; CP: conventional planting without mulching). 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 in which maize was not planted as well as a ridge were established between each plot to prevent water leakage. In the RF system, the ridges and furrows were 60 cm wide and 15 cm high, and the ridge was covered with plastic film (0.9 m wide and 0.008 mm thick); plastic film-covered furrows 70 cm in width were used for the FM treatment. The row spacing of all treatments was 60 cm, and the seeding spacing was as follows: L, 31.8 cm; M, 22.2 cm; and H, 17.1 cm. The treatments are illustrated in Fig. 2. Maize (Dafeng 30) was sown on April 23, 2015, and April 21, 2016, using a hole-sowing machine at a seeding depth of 4–5 cm. Fertilizer application was the same for all treatments: 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, and topsoil fertilizer containing 150 kg ha^{-1} N was applied at the 11-leaf stage (Hanway, 1963, July 10, 2015, and July 8, 2016). The crops were harvested on October 10, 2015, and October 5, 2016.

2.3. Data collection

2.3.1. Soil temperature

Daily variation in soil temperature at 5, 10, 15, 20 and 25 cm depths between individual maize plants was monitored with a mercury-in-glass geothermometer; each measurement was repeated three times. Measurements were obtained at the maize 3-leaf stage (May 22–28, 2015, and May 19–26, 2016), at the 6-leaf stage (June 18–25, 2015, and June 15–23, 2016), at the 11-leaf stage (July 7–15, 2015, and July 6–12, 2016), at the silking stage (July 28 to August 5, 2015, and July 24–31, 2016), at the blister stage (August 24–30, 2015, and August 20–29, 2016) and at the dough stage (September 6–16, 2015, and September 21–30, 2016). Temperatures were recorded on five sunny days at 08:00, 10:00, 12:00, 14:00, 16:00, 18:00 and 20:00 during each growth stage. Average daily temperature was calculated, and the average value for the five days was reported as the soil temperature at each growth stage.

2.3.2. Soil water storage and evapotranspiration

Soil water content in the 0–200 cm soil layer was measured using a 54 mm diameter steel core-sampling tube (Ferraro and Ghersa, 2007) before sowing, and at emergence, 3-leaf, 6-leaf, 11-leaf, silking, and at blister and maturity stages. Samples were collected at every 10 cm from the 0–20 cm soil layer and at every 20 cm from the 20–200 cm soil layer. Sampling within each planting pattern treatment was done according to the following criteria: for the RF treatment, the soil cores were sampled from the middle of a ridge, from the middle of a furrow and between two plants within the same row; for the FM treatment, one sample was obtained between two plants and two samples between two rows (one in the plastic film and the other outside the plastic film); finally, for the CP treatment, two samples were obtained between two rows and one between two plants on the same row. After their wet weight was determined, the soil samples were dried for 48 h in an oven at 105 °C until a constant weight was reached. The soil water content was calculated as the mean of the measurements at the three positions and was replicated three times per plot.

The evapotranspiration (ET) was calculated in accordance with the water balance formula (Huang et al., 2005):

$$ET = P + I + C + (SWS_{t1} - SWS_{t2}) - D - R \quad (1)$$

where P (mm) is the precipitation during the maize growing season, I (mm) is the amount of irrigation ($I = 0$), and C (mm) is the upward flow into the root zone. The groundwater level was approximately 80 m below the soil surface; thus, groundwater flow to the roots could be