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Interactive effects of planting models with limited irrigation on soil water, temperature, respiration and winter wheat production under simulated rainfall conditions

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A B S T R A C T

The development of effective water-saving farming practices have been vitally important for increasing wheat productivity in semi-arid regions of China. Ridge-furrow (RF) rainfall harvesting is a technique for efficient consumption of precipitation that increases water accessibility to crops at critical growth stages. However, this system has not yet been characterized under simulated rainfall conditions with limited irrigation. A two-year field study was carried out from Oct 2015 to May 2017 to investigate the potential role of two planting models: (1) the RF system and (2) traditional flat planting (TF) under three levels of simulated precipitation (1:275 mm, 2: 200 mm, 3:125 mm), with two limited irrigation levels (150 mm or 75 mm). The topsoil (from 5 to 25 cm) temperature and ET were significantly higher under TF planting than in the RF system, which increased both soil moisture between (0–200 cm) and soil respiration rate during different growth stages. The RF system also regulated soil temperature and respiration rate, reduced ET (46%), and prolonged the period of water accessibility which led to exhibited fast and stable seedling establishment. The average grain yield increased by 10.6% and 12.6% for $RF1_{150}$ and $RF1_{75}$, compared to $TF1_{150}$ and $TF1_{75}$, and increased by 18.9% and 22.5% for $RF2_{150}$ and $RF2_{75}$ as compared to $TF2_{150}$ and $TF2_{75}$, while $RF3_{150}$ and $RF3_{75}$ treatments significantly increased by 14.3% and 8.9% as compared to $TF3_{150}$ and $TF3_{75}$, respectively. Average WUE significantly improved by ($P < 0.05$) in $RF1_{150}$, $RF1_{75}$, $RF2_{150}$, $RF2_{75}$, $RF3_{150}$, and $RF3_{75}$ were 53.3%, 56.4%, 75.8%, 85.1%, 68.2% and 75.3% compared to TF planting, respectively. As precipitation increased from 200 to 275 mm there were no significant increases in moisture contents, soil respiration rate, ET, WUE, and grain yield under both planting models. Therefore, we concluded that the $RF2_{150}$ treatment is suitable as a water-saving technology to achieve higher wheat production and WUE in semi-arid agro-ecosystems of China.

1. Introduction

Rainwater is the major water source in rain-fed agro-ecosystems of China and winter wheat crop productivity mainly depends on unpredictable and limited rainfall (Moret and Arrue, 2007). Rain-fed areas in China have annual mean precipitation of 380 mm, and 59% of the precipitation occurs between July and September (Govaerts et al., 2009). In addition, heavy storms in the spring, combined with high solar radiation and air temperature in the summer, increase annual evaporation and soil temperature, but reduce soil moisture contents, which causes water scarcity (Nagaz et al., 2012). Improvement of water saving techniques is required to deal with the inadequate rainwater resources in this region and to improve water use efficiency (WUE) (Richards et al., 2002).

The ridge furrow (RF) precipitation harvesting technique has been used in rain-fed areas in order to solve the problem of water scarcity (Bronick and Lal, 2005). The RF system significantly increases the utilization of rainwater, improves soil water content, and reduces soil temperature and evapotranspiration rate due to increased WUE and soil respiration rate (Hu et al., 2014). Under the RF system the ridges are

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covered with a plastic film creating a precipitation collection zone; the furrows are used as a sowing zone and is not covered with a plastic film (Moret and Arrue, 2007; Jia et al., 2018). The RF technique can increase moisture contents by accumulating water from light precipitation and preserving runoff from heavy rainfall (Lampurlanes et al., 2002). Plastic film mulching also reduces soil evaporation and extends the duration of water accessibility to critical growth stages, thereby improving wheat productivity, WUE, and soil respiration rate (Ali et al., 2017). The RF system increases soil moisture by 5–12% at the 200 cm soil layer depth under simulated precipitation of 230 mm and increases grain yield by 75% (Ren et al., 2008). Therefore, the RF system is an efficient technique for increased use of precipitation and increased crop production in rain-fed regions of China (Malagnoux, 2006).

Limited irrigation (LI) with the RF technique might be a realistic solution to provide water during key crop growth stages (Xiao et al., 2005; Zhang et al., 2017). LI is an efficient strategy for improving winter wheat production (Olesen et al., 2000; Oweis and Hachum 2006). However, excessive irrigation can increase evapotranspiration, dry matter and leaf area per plant, but it does not significantly increase grain yield, WUE and it reduces the soil respiration rate (Kang et al., 2002; Jia et al., 2017). Soil respiration is mainly produced by the microbial oxidation of organic matter and root respiration, and is an indicator of soil quality, and soil moisture content (Govaerts et al., 2009). Wang et al. (2009) studied the effect of limited irrigation on soil respiration rate, and the results revealed that soil respiration rate improved with increasing irrigation, but that over-irrigation inhibited soil respiration. Zhang et al. (2009) reported that heavy rainfall suppressed the soil respiration rate by 33%.

The unnecessary losses of limited irrigation and precipitation lead to reduced winter wheat production in semi-arid agro-ecosystems of China (Wei et al., 2018). Crop cultivation techniques have greatly improved after switching from traditional flat (TF) planting to the RF rainfall harvesting system to increase the productivity of runoff and collect the maximum amount of precipitation, which could increase WUE of natural rainfall (Schwen et al., 2011). Our research group has carried out many trials using the RF technique since the dry-land farming system project started in semi-arid regions of China, whereas earlier studies focused mostly on water regulation (Wu et al., 2015; Kargas et al., 2012), fertilizer application rates (Zhang et al., 2009), and ridge covering mulching materials (Ren et al., 2008). The objectives of the present study is to explore: (1) the effect of RF system on winter wheat grain yield and WUE; (2) the effect of simulated rainfall with limited irrigation conditions under the RF system on soil water contents in various soil layers, soil temperature, ET rate, soil respiration rate, and crop development; (3) the establishment of the befitting rainfall range for rainwater harvesting under semi-arid climate. We expect that this study will completely support the RF system and provide mechanisms for efficient consumption of simulated precipitation as well as limited irrigation in semi-arid agro-ecosystems.

2. Materials and methods

2.1. Experimental site description and design

Field trials were conducted from 2015 to 2017 at Northwest A&F University, Yangling, Shaanxi Province, in China (34°20′N, 108°24′E, 466.7 m above sea level). This site is characterized as a typical semi-arid area with a warm, temperate and continental monsoon climate. The average annual rainfall was 550 mm yr^{-1}, approximately 70% of which occurred from July to September, with an annual average evaporation rate of 1753 mm. The annual temperature average was 12.9 °C, and annual average maximum and minimum temperatures were 42 °C and −17.4 °C. The daily average air temperatures during the winter wheat growing seasons were presented in (Fig. 1). The total duration of sunshine hours were 2196 h per year, with a frost-free period of 220 days. The soil at the trial site was a loess soil with a pH of 7.73, and a mean bulk density of 1.37 g cm^{-3}. The two-year averages of NPK were 41.3 mg kg^{-1} N, 8.56 mg kg^{-1} P, and 100 mg kg^{-1} K. The organic matter content of the 0–20 cm soil layer was 11.29 g kg^{-1}.

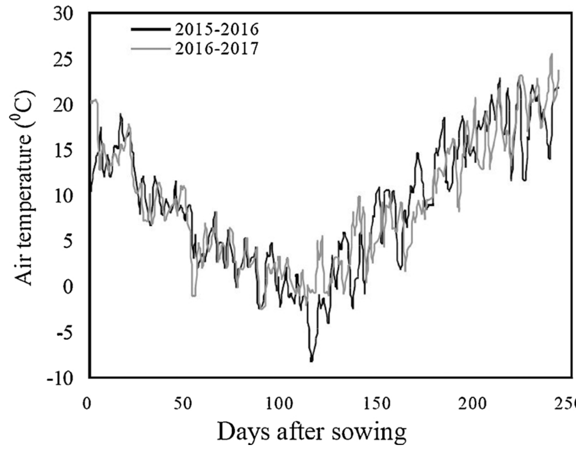

Fig. 1. The daily average air temperature during the winter wheat growing seasons in experimental fields at Northwest A&F University, Yangling, Shaanxi Province, China in 2015–2016 and 2016–2017.

The field study was performed under three large-scale waterproof sheds. The inside shed size was 3 m (height) × 15 m (width) × 32 m (length). The mobile waterproof sheds were used to manage natural rainfall on rainy days. The research trial consisted of two planting patterns (RF: ridge furrow rainfall collection, and TF: traditional flat planting) with three precipitation levels (1:275 mm, 2:200 mm, 3:125 mm) and two limited irrigation (150 mm and 75 mm) levels in a randomized complete block design (RCBD) with three replications. Half of the limited irrigation was supplied on December 12, 2015 and December 15, 2016 (before the re-wintering stage) and the other half was supplied on March 28, 2016 and March 25, 2017 at the jointing stage with the help of a precise water meter. The limited irrigation volumes of 150 and 75 mm were measured according to the irrigation area. The irrigation area for the TF planting treatment was 6.3 m^2 (2.0 m × 3.15 m) and the irrigation volumes were 0.95 and 0.47 m^3 under 150 and 75 mm, respectively. The irrigation area of the two furrows under the RF technique was 3.78 m^2 (1.2 m × 3.15 m) and the irrigation volumes of the two furrows were 0.57 and 0.28 m^3. The RF technique had a ridge height of 15 cm with furrow and ridge widths of 60:40 cm. A plastic film with 0.008 mm thickness was used to cover all ridges with hidden edges of 4–5 cm deep in the soil. Four rows of wheat were planted in furrows (Fig. 2). The width and length of each plot was 2.0 m × 3.15 m. Each plot was separated by 17 cm thick concrete walls to prevent inter exchange of soil moisture content. Weeds were controlled manually during each winter wheat growing season.

Wheat cultivar Xinong 979 was planted at the rate of 2,250,000 seeds ha^{-1}. Seeds were planted with an inter-row space of 20 cm on October 15 in 2015 and on October 10 in 2016. Wheat was hand harvested on June 2 in 2016 and on May 27 in 2017. All of the nitrogen (urea) and phosphorus (diammonium phosphate) were applied at the time of planting at the rates of 225 and 75 kg ha^{-1}, respectively. In this study, simulated rainfall was used and no natural rainfall was allowed during the wheat growing season (Fig. 3). Simulated rainfall was applied according to methods from previous studies (Liu et al., 2013; Ali et al., 2017). Complete detail of the rainfall conditions can be seen in Table 1. In this rainfall simulator study, the amount of rainwater measured under field conditions was reasonably similar to natural rainfall amounts.

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