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Cultivation techniques combined with deficit irrigation improves winter wheat photosynthetic characteristics, dry matter translocation and water use efficiency under simulated rainfall conditions

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A B S T R A C T

Determining the effect of different cultivation techniques on photosynthetic characteristics, dry matter translocation and water use efficiency (WUE) will provide insight for the development of water-saving farming systems and exploiting the photosynthetic characteristics of winter wheat under deficit irrigation. In the current study, a mobile rainproof shelter was used to explore the potential role of two cultivation techniques: (1) the ridge and furrow precipitation harvesting technique (R); and (2) the flat cultivation technique (F), under two levels of deficit irrigation (150, 75 mm) levels and three levels of rainfall (1: 275, 2: 200, 3: 125 mm). We found that cultivation technique had a significant effect on rainfall water harvesting and enhanced soil water content under all levels of deficit irrigation and simulated precipitation. Under the R cultivation technique with 150 mm deficit irrigation and 200 mm simulated rainfall level can efficiently improve moisture content, thus significantly increased the average net photosynthetic rate (Pn) (10.4%), stomatal conductance (Gs) (27.2%), transpiration rate (Tr) (9.3%), intercellular CO_2 concentration (Ci) (4.0%), dry matter translocation (31.6%), translocation efficiency (15.2%), pre-flowering assimilate translocation to grain (10.6%), grain yield (18.9%), WUE (75.8%) and economic return (12197 Yuan ha^{-1}) of winter wheat, while significantly reduce (32.7%) ET rate compared with F cultivation technique. The R cultivation technique significantly improved photosynthetic characteristics such as Pn, Gs, Tr, Ci and dry matter translocation in the later growth stage (grain filling stage) compared with the F cultivation technique at each irrigation and rainfall level. Furthermore, these photosynthetic parameters were positively correlated with dry matter translocation, soil water content and grain yield. The greatest improvement in the photosynthetic characteristics, translocation efficiency, WUE, grain production and economic return was achieved when using the R cultivation technique with 150 mm deficit irrigation and 200 mm simulated rainfall ($R2_{150}$). Therefore, we conclude that the $R2_{150}$ treatment is the best water-saving management strategy for growing wheat crops in rain-fed farming systems.

1. Introduction

In semi-arid regions of China, water shortages, low rainfall and drought occur regularly during wheat growing periods and are the major bottlenecks affecting wheat production and water use efficiency (WUE). Adverse dry weather during the winter wheat growing season is like to increase due to projected global ecological change and could have a harmful effect on crop production (Kang et al., 2002; Richards, 2000). Water deficiency is not only a serious ecological issue but a limiting factor affecting crop growth and production (Kang et al., 2000; Pampino et al., 2006). The negative effects of water deficit on crop production along with the cost of pumping of irrigation water, insufficient facilities for irrigation manufacturing and restricted water sources have forced several farmers to use irrigation water more efficiently (Cakir, 2004; Du et al., 2010). In fact, the only way to sustain cereal production in semi-arid regions is to efficiently use irrigation water, develop water-saving farming strategies and improve WUE (Kang et al., 2002). One important water-saving agricultural strategy is

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the use of deficit irrigation with plastic film mulching, which decreases vegetative growth and increases crop yield and WUE (Fabeiro et al., 2001; Du et al., 2010). Thus, it is essential to study crop productivity and WUE of winter wheat under different cultivation patterns and levels of deficit irrigation to develop water-saving agriculture practices that enhance crop yields and rainwater management in semi-arid regions.

Rainfall is one of the main water resources in rain-fed regions of China, and rain-fed farming systems occupy 80% of all cultivated land (Han et al., 2004). However, erratic and inadequate rainfall significantly affects wheat production and occasionally results in total crop failure. Thus, it is essential to economically use erratic precipitation and increase water storage in this region (Liao et al., 2003). The ridge and furrow rainfall water collecting system with plastic film mulching is one of the most efficient techniques to increase wheat production and WUE in rain-fed regions (Wang et al., 2008). In recent years, plastic film has been widely adopted in the rain-fed regions of China to conserve rainwater in root zone of wheat crops (Tian et al., 2003). A previous study revealed that plastic film mulching can decrease soil evaporation and enhance soil water storage and crop production (Zhang et al., 2005). Leib et al. (2006) also reported that plastic film and supplemental irrigation significantly increases wheat production and net profits compared with flat planting without plastic film mulching.

Photosynthetic characteristics, dry matter translocation (DMT), grain yield and WUE depend on the soil water content (SWC) at various growth stages (Qiu et al., 2008; Abbasi et al., 2014). There have been several studies of the effects of moisture content on the net photosynthetic rate (Pn), DMT and grain yield of wheat (Yang et al., 2000; Luo et al., 2011). It is generally recognized that increasing SWC improves Pn, which contributes to increased grain filling rate and crop production (Wu et al., 2014; Cui et al., 2015). Previous studies revealed that water scarcity during the flowering stage can negatively impacts Pn, reduces the period of photosynthesis and considerably increases flag leaf senescence (Yang et al., 2000; Wu et al., 2014). Flag leaf senescence due to water deficit may in turn reduce the contribution of pre-flowering assimilates to grains (CPAG) (Xue et al., 2006). During senescence the degradation of the inner structure of the plant and stored matter is accelerated, so the premature senescence of flag leaves due to drought may benefit the mobilization and re-translocation of the reserves accumulated pre-flowering (Yang et al., 2000). Winter wheat is also very susceptible to drought stress during the reproductive growth stage (Ge et al., 2012). Photosynthesis, which is the most essential process affecting crop production in semi-arid regions of China, is inhibited by water stress (Chen and Hao, 2015). Under plastic film mulching winter wheat efficiently utilized rainwater and had improved photosynthesis and dry matter accumulation (Guoth et al., 2009; Liu et al., 2011).

WUE_i is related to the ability of plants to absorb maximum concentrations of carbon (high Pn) and restrict water loss through the control of the stomatal aperture which knows is transpiration rate (Tr) (Araus et al., 2002; Monneveux et al., 2006). In addition, WUE_i is strongly associated with Pn and transpiration efficiency (TE), which can be affected by deficit irrigation (Flexas et al., 2013).

In this study, we conducted a field trial under a large mobile rainproof shelter to study the effects of different cultivation techniques with different levels of deficit irrigation and simulated rainfall on photosynthetic characteristics, dry matter accumulation, crop yield and WUE. The aims of this study were to (1) examine the effects of different cultivation techniques and different levels of deficit irrigation on photosynthetic characteristics and remobilization of pre-flowering assimilates during key growth stages of wheat, and to (2) evaluate grain yield and WUE under simulated rainfall conditions. Our findings provide valuable information that can be used to improve photosynthetic characteristics, DMT, yield and WUE when growing winter wheat in rain-fed regions of China.

2. Materials and methods

2.1. Study site description

The field study was performed during the 2015–2016 and 2016–2017 growing seasons at Northwest A&F University, Shaanxi Province, China (34°20′N, 108°24′E). The experimental site is located 466.7 m above sea level in a warm, temperate semi-arid region with an annual mean temperature of 12.9 °C, and annual low and high temperatures of −17.4 °C and 42 °C, respectively. The annual evaporation rate is 1753 mm. The total duration of daylight is 2196 h per year, with a frost-free period of 220 days per year. The mean soil bulk density was 1.37 g cm^{-3}. The averages across two years of available NPK data were 39.4 mg kg^{-1}, 7.98 mg kg^{-1} and 99.94 mg kg^{-1}. In the 0–20 cm soil layer, the soil organic matter content was 10.88 g kg^{-1} and the pH was 7.80.

2.2. Experimental design and treatments

The field study was performed under mobile waterproof sheds 3 m (height) × 15 m (width) × 32 m (length) in size to manage natural rainfall. The research trial consisted of two planting patterns, (1) the ridge and furrow precipitation harvesting technique (R); and (2) the flat cultivation technique (F), under two deficit irrigation (150, 75 mm) levels and three rainfall (1: 275, 2: 200, 3: 125 mm) levels. Plants were grown in a randomized complete block design (RCBD) with four replicates. Using a precise water meter, half of the deficit irrigation was supplied on December 12, 2015 and December 15, 2016 (before the rewintering stage), and the other half was supplied on March 28, 2016 and March 25, 2017 at the jointing stage. The deficit irrigation volumes for the 150 and 75 mm treatments were determined according to the irrigation area. The irrigation area for the F cultivation treatment was 6.3 m^2 (2.0 m × 3.15 m), and the irrigation volume was 0.95 and 0.47 m^3 for the 150 and 75 mm irrigation levels, respectively. The irrigation area under the R treatment of the two furrows was 3.78 m^2 (1.2 m × 3.15 m) and the irrigation volumes were 0.57 and 0.28 m^3. For the RF technique, a ridge height of 15 cm was used with a furrow to ridge width ratio of 60:40 cm. A plastic film was used to cover all ridges with hidden edges 4–5 cm deep in the soil. Four rows of wheat were sown in furrows (Fig. 1). The length and width of each cemented pond plot was 3.15 m × 2.0 m with and 3 m in depth, and plots were split divided by 17 cm- thick concrete walls to avoid the exchange of soil water contents between plots. Weeds were controlled manually during each growing season.

Wheat cultivar (Xinong 979) was sown at the rate of 2.25′ 10^6 seeds ha^{-1}. The 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. Nitrogen (urea + diammonium phosphate) at 225 kg ha^{-1} and phosphorus (diammonium phosphate) at 75 kg ha^{-1} were applied at the time of planting. The levels of simulated rainfall were determined based on the distribution of rainfall in the semi-arid regions of northern China over the past 48 years.-years period (1966–2014). Three total amounts of simulated rainfall, 125, 200, and 275 mm, corresponding to light (1), moderate (2), and heavy (3) simulated rain levels, were applied as described in a previous study (Ali et al., 2017). In this study, a precipitation simulator was used to provide the crop water, and no natural precipitation was allowed during the wheat growing season (Fig. 2). Complete details of the precipitation conditions can be seen in Table 1. The amount of rainwater used in this study was similar to natural rainfall amounts.

2.3. Sampling and measurement

2.3.1. Soil water content

The SWC was calculated at sowing, jointing, flowering, grain filling