Agricultural Water Management 209 (2018) 44–54

Contents lists available at ScienceDirect

Agricultural Water Management

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

Tillage and deficit irrigation strategies to improve winter wheat production through regulating root development under simulated rainfall conditions

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ARTICLE INFO

Keywords:
Cultivation modes
Rainfall simulator
Grain yield
Root morphology
Root respiration rate
Soil water content

ABSTRACT

Knowledge of rooting systems and soil water status across rooting zones is important for stabilizing agricultural productivity in the semi-arid regions of China. In the present study, a mobile rainproof shelter trial was performed to find out the effects of cultivation mode on the temporal and spatial root growth distribution, soil water content, root respiration rate, and grain yield during 2015–2016 and 2016–2017 growing seasons. The two cultivation modes were: (1) the ridge furrow (RF) rainfall harvesting technique; and (2) traditional flat planting (TF). In addition, three simulated rainfall (1: 275, 2: 200, 3: 125 mm) and two deficit irrigation (150, 75 mm) levels were used. Our results showed that different cultivation modes with simulated precipitation levels significantly improved moisture content for wheat growth, improved root growth, and provided favourable conditions for higher wheat production. The RF_{150} treatment with 200 mm rainfall significantly increased morphology of the wheat rooting system, especially in the top 40 cm soil layer compared with TF cultivation. The RF_{150} treatment significantly increased root dry weight (47%), root tissue density (6.7%), root fineness (4.8%), root length ratio (20.3%), root mass ratio (27.3%), and grain yield (18.9%) of wheat at 200 mm rainfall than that of $TF2_{150}$ treatment. Root weight density, root length density, root surface area density, and root diameter were significantly higher under RF_{150} treatment with 200 mm and 275 mm precipitation in the 40 cm soil layer and reached maximum values at the flowering stage. The root dry weight, root respiration rate, and grain yield were significantly improved under $RF2_{150}$ treatment, but there were no significant differences when the rainwater increased from 200 to 275 mm under both cultivation modes. Therefore, we suggested that the $RF2_{150}$ treatment is a suitable water saving strategy to improve temporal and spatial root growth distribution, resulting in higher grain yield in a dry-land farming system.

1. Introduction

Water availability is the most essential limiting factor for wheat crop production in rain-fed areas of China (Gan et al., 2008). In these regions, precipitation is the most important water source for agricultural development and production (Du et al., 2015), and inadequate or unpredictable rainfall often results in low crop productivity and sometimes total crop failure (Wang et al., 2011a). The seasonal evapotranspiration (ET) rate in these regions ranges from 750 to 1000 mm, which is considerably higher than the annual precipitation rate (250–550 mm) (Ren et al., 2010). However, 70% of groundwater resources in these areas are used for agricultural production (Zhao et al., 2013). The water table has been affected by deep irrigation and misuse of groundwater resources (Currell et al., 2012), and has decreased by 0.5–3 m/year in the northwest part of China over the last 20 years (Du et al., 2015). Thus, it is essential to apply efficient water saving agriculture strategies to not only efficiently store soil water from small precipitation events, but also efficiently store rainfall water in root zones of crop for use during drought phases to attain higher crop productivity (Shao et al., 2011).

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https://doi.org/10.1016/j.agwat.2018.07.007
Received 1 March 2018; Received in revised form 28 June 2018; Accepted 12 July 2018
0378-3774/

Table 1
The key properties of the soil layers (0–60 cm depth).

Soil layer (cm)	SOM ($g\ kg^{-1}$)	AN ($mg\ kg^{-1}$)	AP ($mg\ kg^{-1}$)	AK ($mg\ kg^{-1}$)	TN ($g\ kg^{-1}$)	BD ($g\ cm^{-3}$)	P (%)	SM (%)	pH
0–20	9.55	60.7	15.8	155.9	1.13	1.37	49.5	37.1	8.1
20–40	8.23	43.5	8.4	120.6	0.95	1.39	49.3	36.2	8.3
40–60	7.34	45.9	5.9	101.8	1.07	1.41	45.9	38.8	8.3

SOM: soil organic matter; AN: available nitrogen; AP: available phosphorus; AK: available potassium; TN: total nitrogen; BD: bulk density; P: porosity; SM: saturated moisture.

Precipitation harvesting techniques with plastic film mulching have been implemented in rain-fed regions of China to store rainfall for later crop use (Wang et al., 2009). Several practices have been used to trap rainfall water (Wang et al., 2011b). Of these practices, the ridge furrow (RF) precipitation harvesting method with plastic film has been recommended as one of the most efficient to optimize crop productivity (Chakraborty et al., 2008). The ridge covered with plastic film mulch can conserve more rainwater, extend the period of water accessibility, and improve crop productivity by saving rainwater from light precipitation, and by retaining surface runoff from heavy precipitation as compared with traditional flat planting (Wang et al., 2009). The RF system with ridge covered with plastic film significantly increased water content, crop productivity, and WUE in semi-arid zones (Xiao et al., 2007). But, very limited research has been conducted on root growth and its association with soil moisture availability in winter wheat under the RF system with plastic film. To attain higher crop productivity in semi-arid regions, knowledge of root morphology is essential (Liu et al., 2011). Roots of the winter wheat crop have a significant role in sensing ecological modifications and conveying that information to the aboveground parts of the plant to provoke suitable adaptive responses, such as changes in root morphology and metabolic activity to optimize the consumption of limited water resources (Chaves et al., 2003).

The roots of the winter wheat crop are the most significant organ for nutrient and rainwater uptake and have a vital role in the plant and soil ecosystem (Spedding et al., 2004; Zhang et al., 2014). Thus, the relationships of soil water and crop rooting systems have been studied more intensely in recent years. Soil water has been found to enhance the accessibility of nutrients, and nutrients enhance root growth and crop productivity (Besharat et al., 2010). Root growth and distribution heavily influence water and nutrient uptake in winter wheat crops (Li et al., 2010). The main root morphological features of winter wheat are root weight density, root length density, root surface area density, root diameter, and root respiration rate, all of which directly affect the function of the whole root system and indirectly affect aboveground biomass accumulation (Xia et al., 2005; Fageria, 2004).

Water scarcity decreases uptake of nutrients and limits root growth and distribution (Araki et al., 2012). Corn grown under the RF system with deficit irrigation conditions produced higher root length, root diameter, and root weight density, which improved nutrient and water uptake capacity, and thus decreased water deficit stress and improve corn yields (Shen et al., 2013). The RF system with simulated precipitation conditions significantly affected soil water storage in corn, significantly increased root penetration, and thus produced higher root length density, and increased soil and root respiration rates, which finally improved characteristics of spike and maize production (Gan et al., 2013). Root length is an important aspect for assessing the RF cultivation mode under deficit irrigation (Li et al., 2001; Mosaddeghi et al., 2009). However, there have been limited studies on the mechanisms to improve wheat productivity through modify root growth and root respiration rate under the RF mode with simulated rainfall and deficit irrigation conditions. Thus, the objectives of this field-based trial were to: (i) determine temporal and spatial root morphological growth of winter wheat under different cultivation modes with deficit irrigation; (ii) estimate soil water contents at different depths, root and soil respiration rates under simulated rainfall conditions; and (iii) study the interactive effect of cultivation modes with deficit irrigation on root growth, root respiration rate, moisture content and production of wheat under simulated rainfall conditions, and to reduce drought in a rain-fed regions.

2. Materials and methods

2.1. Study site description

The field study was performed during 2015–2017 at the Northwest A&F University, Shaanxi Province, China (34°20′N, 108°24′E). The experimental site was 466.7 m above sea level. The trial site is located 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 was 1753 mm. The total duration of daylight was 2196 h per year, with a frost-free period of 220 days per year. Annual average rainfall of 380 mm per year occurred between July and September. Selected soil physico-chemical properties of the experimental site for the soil layers in the 0–60 cm depth are shown in Table 1.

2.2. Experimental design and treatments

The field study was performed under waterproof sheds. The size inside the shed was 3 m (height) × 15 m (width) × 32 m (length). The mobile waterproof sheds were used to manage natural rainfall. The precipitation level partitioning was derived from the spatial and temporal characteristics of the precipitation distribution in the semi-arid areas of northern China over the past 48-years period (1966–2014). In the precipitation simulation, three seasonal rainfalls, 275, 200, and 125 mm, corresponded to heavy, moderate, and light simulated rain levels. In this study, simulated rainfall levels, were applied as described in a previous study (Ali et al., 2017) and no natural precipitation was allowed during the wheat growing season. Complete detail of the precipitation events can be seen in Table 2. The amount of rainwater used in this study was reasonably similar to natural rainfall amounts. 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, and 3: 125 mm) and two deficit irrigation (150 mm and 75 mm) levels 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 re-wintering stage) and the other half was supplied on March 28, 2016 and March 25, 2017 at the jointing stage during two growing season o f winter wheat. The deficit irrigation volumes for 150 and 75 mm were measured according to the irrigation area. The irrigation area for the TF 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 under 150 and 75 mm, respectively. The irrigation area under the RF technique of the two furrows 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 used a ridge height of 15 cm with a ratio of furrow to ridge widths 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