Field Crops Research 216 (2018) 63–74

Contents lists available at ScienceDirect

Field Crops Research

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

Yield loss compensation effect and water use efficiency of winter wheat under double-blank row mulching and limited irrigation in northern China

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A R T I C L E I N F O

Keywords:
Grain yield and growth parameters
Limited irrigation
Mulching pattern
Water use efficiency (WUE)
Winter wheat

A B S T R A C T

Maize straw residues as a surface mulching material would be an effective soil water-saving practice in wheat production for a wheat-maize rotation system in northern China. Additionally, combining a mulching pattern and limited irrigation could play an important role in enhancing the productivity of winter wheat. Therefore, open field experiments were carried out during 2012–2014 to study soil water content in depth, water use efficiency (WUE), soil temperature, wheat grain yield and root parameters under a mulching pattern [each-row mulching (ERM) and double-blank row mulching (DRM) with three mulching masses of 0. 4.5 and 9.0 t ha^{-1}] and limited irrigation [no irrigation (I_0) and one-time irrigation in winter (I_1)].

Results indicated that wheat yields increased (mean 3.3%) or decreased (mean 5.4%) a little under ERM groups with no irrigation. Irrigation for each row of mulch increased the wheat yield (mean 8.8%). With or without irrigation, yields under DRM_0 were lower compared to ERM_0, whereas, $DRM_{4.5}$ and $DRM_{9.0}$ had a higher grain yield than $ERM_{4.5}$ and $ERM_{9.0}$ (mean 25% under I_0 and 18.8% under I_1) as well as DRM_0 (mean 24.1%). The DRM patterns with a high yield could have an equal effect with irrigation in winter. Additionally, irrigation could enhance the effects of DRM on wheat yield increase (mean 6.87 t ha^{-1}in $DRM_{4.5}$ and 7.06 t ha^{-1} in $DRM_{9.0}$). Effective tillers and above-ground biomass would be the key factors for determining wheat yield, especially under certain mulching patterns, although these effects were not reflected in wheat roots.

Mulching on soil temperature had a more significant difference in an early growth period than the later stages of wheat. An additional feature was that the DRM pattern had a persistent heat preservation effect in the re-growth stage, while there was a lower soil temperature in ERM groups in this stage when there was no irrigation. Mulching managed to shorten the period of negative accumulated temperatures of wheat (mean of 7 days under ERM and 15 days under DRM) under I_0. Winter water irrigation enhanced the shorten effect to a certain extent. Mulching had a more significant water conservation effect in the overwinter stage with lower precipitation and higher soil evaporation. Soil water content under DRM groups was richer than ERM groups in the late growth stage, when there was lower plant density and evapotranspiration, but there was a higher yield and WUE (with a mean of 18.6% under I_0 and 20.3% under I_1).

The results suggest that the DRM pattern optimizes soil temperature, water content, balance roots and group effects as well as increasing wheat yield. Thus, this approach could be a better field management option for wheat growth and yield production under the limitations of water in northern China.

1. Introduction

In the northern part of China, it is popular to use double cropping with winter wheat and summer maize in agricultural practice, and irrigation is required to obtain a high yield for both crops (Li et al., 2008, 2012a,b; Chen et al., 2015). The average annual water use of the two crops is 850 mm, whereas the annual average rainfall is 450–500 mm (Chen et al., 2007; Chai et al., 2014). Furthermore, the rain season of a year is mainly concentrated from July to September, which is also the maize growth period, whereas rainfall in the wheat growth period is approximately 200 mm (Wang et al., 2012), induces low water use in winter wheat and leads to high soil water evaporation (He et al., 2016).

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https://doi.org/10.1016/j.fcr.2017.11.009
Received 6 April 2017; Received in revised form 26 July 2017; Accepted 9 November 2017
0378-4290/

Although wheat is widely cultivated in regions with relatively moist winters and springs, precipitation is mostly not enough for optimum yields, and therefore irrigation is necessary (Chen et al., 2015). In a study conducted by Chen et al. (2007), 70% farmers irrigated their fields during only one season (winter or spring) during the whole growth period for winter wheat, whereas 30% of farmers would irrigated their fields during two seasons (winter and spring) or more, due to deficit irrigation conditions and economic cost. Furthermore, the cost of pumping for irrigation led many farmers to reduce their use of irrigation (Gupta et al., 2016). Therefore, it is significant for the future sustainable development of the wheat production system to produce more wheat with the minimum amount of irrigation water (Ali et al., 2007; Abd EI-Wahed and Ali, 2012; Li et al., 2016; Tari, 2016). Additionally, it is critical to achieve the largest possible increase of winter wheat and water use efficiency to adopt water-saving technologies. The combined practice of limited irrigation at some growth stage and mulching appears to be very promising for achieving this goal (Igbadun et al., 2012; Singh et al., 2011a).

Limited irrigation is one of the most important aspects of water-preservation in irrigated agriculture (Li et al., 2013; Ali et al., 2007; Lv et al., 2010, 2015), for potential ET and maximum yield (Tari, 2016) that can increase irrigation efficiency and opportunity cost of water then increase net farm income (English, 1990; Ali et al., 2007). However, mulching could be beneficial in terms of reducing the rates of water loss from the soil surface as well as for meeting irrigation requirements and facilitating moisture distribution, which could influence the irrigation schedule (Fan et al., 2014; Li et al., 2012a,b; Singh et al., 2011b; Abd EI-Wahed and Ali, 2012; Gupta et al., 2016). Combination of irrigation with mulch technology can lead to better uptake of water by wheat and reduce the amount of irrigation that is required (Ma et al., 2016).

However, mulch has not always increased yields because of many factors that can determine effects on wheat development, especially for the interaction between mulch and irrigation (Chen et al., 2007; Chakraborty et al., 2008; Singh et al., 2011c; Ram et al., 2013; Chen et al., 2013a; Zhang et al., 2015). The main cause for reduced yield in winter wheat is the reduction in spikes due to straw mulching (Chen et al., 2013b) because mulch has a negative effect on plant density that further extends to population development (Liu et al., 2014). Studies by researchers, such as Li et al. (2006) and Singh et al. (2011c), have noted that mulched winter wheat did not grow as well as those without mulch during periods of overwintering and regrowth. However, crop growth is slowed down by a low degree of mulch after the regrowth period according to Chen et al. (2007, 2013b). Therefore, determining how to overcome the negative effects of straw mulch and increasing winter wheat yield while reducing the total water use is very critical for a high-yield and water-efficient application of straw mulch.

Blank mulching, which is a pattern of planting 2–5 rows of wheat with blanks mulched with plastic film, has been explored by many researchers (Chen et al., 2015; Zhang et al., 2016; Dang et al., 2016). Biologically, the pattern reduces the area of contact between straw mulch and wheat plants. Blank mulching weakens intraspecific competition, which allows plants to occupy a more ecological niche due to the reduced density per unit area (Liu et al., 2015). Chen et al. (2015) indicated a ridge-furrow framework in which the ridge was covered with plastic film combined with straw, and wheat was planted in the furrow. Li et al. (2016) and Zhang et al. (2013) proposed the practice of combining a ridge with plastic film mulching with two rows of wheat combined with a row of mulching. According to Li et al. (2015), a wide-precision planting practice with 2–4 rows was also proposed to improve winter wheat yield. Both practices were effective for increasing the wheat yield and WUE due to its high moisture and favorable topsoil temperature during the seedling establishment period. Additionally, double mulching with plastic film and crop straw has been the focus of study for many researchers (Yin et al., 2016; Liu et al., 2016). However, very few research studies have been conducted about the application of simple straw to these planting practices.

In this study, we propose a method of alternating planting and straw mulching in which the seeding rate remains the same but one in three rows is left blank for mulch while the other two are used for planting. This method may compensate for the loss of yield caused by straw mulching in each row to some extent, which improves both the output of winter wheat and WUE. Therefore, the field study aimed to (a) investigate the coupling effect of the straw mulching pattern and irrigation on soil temperature and water condition; (b) measure the wheat yield, water use and root parameters; and (c) determine an appropriate straw mulching pattern and irrigation mode for maximum WUE and wheat yield in North China.

2. Materials and methods

2.1. Experiment site

The field experiment was conducted at a location of 36°19′N latitude and 111°49′E longitude in Han Village in Shanxi Province of northern China during 2012–2013 and 2013–2014. The climate of this area was semi-arid and semi-humid. The mean annual temperature was 9.0–12.9 °C, and the frost-free period was 127–280 days. The long-term mean annual rainfall at the site was 420.1–550.6 mm with 60% of rainfall occurring from July to September.

2.2. Soil characteristics of the experimental site

The soil of the experimental site was Calcareous cinnamon, which is a moderately well-drained loamy soil with a deep profile at the station. The characteristics of the experimental site are displayed in Table 1.

2.3. Experimental design and methods

2.3.1. Experimental design

The experiment was carried out in a split plot design that has two irrigation managements in main plots and three amounts of maize straw mulch in sub-plots with three replications of each amount. The irrigation management conditions included no supplemental irrigation (I_0), irrigation only during the overwintering stage (I_1, 85 days, 2012–12–25 in 2012–2013 and 2013–12–29 in 2013–2014), with no irrigation as the control. The irrigation water was deep ground water collected from a pump near the experimental site. The total volume of irrigation water was all controlled at 120 mm. Between two irrigation plots, there was a 2.5-m-wide zone without irrigation to minimize the interference of two adjacent plots. $ERM_{4.5}$ and $ERM_{9.0}$ represented each row mulched with 4.5 t ha^{-1} and 9.0 t ha^{-1} mulch, and $DRM_{4.5}$ and $DRM_{9.0}$ represented

Table 1
Soil properties of the experimental field before the start of experiment.

Depth (cm)	pH	EC (μs cm^{-1})	OM (g kg^{-1})	TN (mg kg^{-1})	AP (mg kg^{-1})	AK (mg kg^{-1})	BD (g cm^{-3})
0–20	8.45	141.4	15.20	1.28	10.6	117.0	1.34
20–40	8.17	120.3	11.22	0.86	7.67	88.2	1.43

EC: electric conductivity; OM: organic matter; TN: total nitrogen; TP: total phosphorus; TK: total potassium; AN: alkali-hydrolyzale nitrogen; AP: available phosphorus; AK: available potassium; BD: soil bulk density.