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The coupled impact of plastic film mulching and deficit irrigation on soil water/heat transfer and water use efficiency of spring wheat in Northwest China

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ABSTRACT

To investigate the influences of plastic film mulching and deficit irrigation on water use efficiency (WUE) of spring wheat, a 2-year field experiment was conducted from 2014 to 2015 in a semi-arid region of Northwest China. The experiments involve ten treatments and each have two replicates, including two levels of field mulching, i.e., no mulching (M0) and clear plastic film mulching (M1), and five irrigation levels, including the full irrigation treatment (W1) and four deficit irrigation treatments (W2–W5). The variation of soil moisture and temperature at different soil depths were monitored during the entire growing season, together with crop physiological index and yield. The results showed that the average soil temperature at 10 and 20 cm soil depth under film mulching were improved by 5.5%–9.3% compared with no mulching during the entire growing season, and were improved by 8.2%–16.5% during the early stage, i.e., 0–40 DAP (day after planting). Film mulching could help decrease soil evaporation and conserve the water in topsoil layers during the early stage of spring wheat growth, while in the middle stage the crop tended to consume more soil water in the root zone under film mulching condition. Compared with the cases with no mulching, the stages of emergence, tillering, jointing, heading, and milk ripe occurred 3, 2, 2–3, 2–7, 3–7 days earlier under mulched cases. The highest WUE in 2014 was 1.48 kg m^{-3} achieved under W5M1 treatment, and the highest WUE in 2015 was 1.43 kg m^{-3} achieved under W3M1 treatment. Generally, film mulching enhanced the soil temperature especially in the early stage, which consequently led to the advancement of growth stage and the improvement of WUE for spring wheat in this area. The combination of film mulching and some degree of deficit irrigation could reduce water loss and keep crop yield at a desirable level. Therefore with appropriate disposal techniques, field mulching tends to be an effective practice to improve water productivity in arid and semiarid agro-ecosystems of China.

1. Introduction

With the global climate change and the influence of human activity, severe water shortage and uneven distribution of water resources have become the greatest social and environmental challenge of the 21 st century in the world (Karthe et al., 2014). Water shortage is one of the major constraints to agriculture production in the arid land of northwest China, where the annual rainfall ranges from 40 to 200 mm. Shiyang River Basin is one of the three largest continental river basins in China, with the largest population, the highest level of exploitation and utilization of water resources, and the serious contradictions between water and ecological environment in the Hexi inland river basin in Gansu province. In 2014, agricultural irrigation water consumption was 1.488 billion m^3, accounting for 62.78% of the total water consumption in the Shiyang River Basin (Lei, 2015). Spring wheat, one of the main grain crops in this area, has a high seasonal water requirement for yields. Water turn to be an important input and the most limiting factor for achieving high crop yield. Therefore, efficient use of irrigation water under limited precipitation should be considered for the purpose of saving water as well as improving production.

Film-mulching techniques have been widely used for grain crops, fruit trees and vegetable crops, etc. (Kasperbauer, 2000; Li et al., 2004a,b). Previous research indicated that film mulching can increase the soil temperature, reduce soil evaporation, promote precipitation infiltration (Carter and Miller, 1991; Xie et al., 2005; Anikwe et al., 2007; Li et al., 2013a,b), and improve crop yield as well as the water use efficiency (Horton et al., 1996; Tarara, 2000).

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Over 90% of water used in agriculture is lost through evapotranspiration (ET) (Leuning et al., 2008; Liu et al., 2012). During the wheat growing season, evaporation (E) accounts for 30–60% of ET without mulching on the soil (Gregory et al., 1992), and it can be decreased by 55% with film mulching on the soil (Xie et al., 2005). In northwest China, film mulching has become an effective technique for the local water-saving. Yi et al. (2010) conducted various water management practices for achieving favorable grain yield with high water use efficiency (WUE) of spring maize, and found that film mulching increased ET, improved grain yield, and enhanced WUE by about 23–25%. Zhao et al. (2014) suggested that ridge-furrow irrigation with full film mulching could advance emergence by 8.1–11.7 days, improve WUE and tuber yields of potato in the semi-arid Northwest China. Wang et al. (2015) found that film mulching could increase the soil temperature at 10 cm depth by 2.3 °C before July and nearly 1.2 °C after July, and film mulching with basal fertilizer could increase the yield of maize by 10.61%, 9.48%, and 15.36% over three consecutive years in the Loess Plateau of China. Liu et al. (2016b) showed that film mulching led to higher soil water content during the dry season (winter and spring), for dry-land crop production on the Loess Plateau in China. For instance, the volumetric soil water content increased by 3.5% at depths of 0–20 cm in winter wheat farmland, and by 4.0%–6.0% at depths of 0–80 cm in maize/potato farmland. These studies mainly focus on the impact of film mulching on the soil temperature, the soil moisture, and/or the crop yield, for crops like maize, potato, winter wheat, etc.

Until now, there has been little quantitative experimental research on the coupled effects of film mulching and various irrigation treatments on water/heat transfer, the crop growth and WUE in farmlands, especially for spring wheat, one of the main crops in Northwest China. The main objectives of this research is to: (1) compare the effects of field film mulching and non-mulching on soil temperature during the growing season; (2) investigate the coupled effects of deficit irrigation and field mulching condition on water use, spring wheat growth and yield; and (3) determine an optimum irrigation strategy with film mulching for achieving high WUE of spring wheat in the local region.

2. Materials and methods

2.1. Experimental site description

The experiments were conducted during 2014 and 2015 at Shiyang Experimental Station for Water-saving in Agriculture and Ecology of China Agricultural University, located in Gansu Province of Northwest China (N 37°52, E 102°50, altitude 1581 m). The mean annual temperature was 8 °C. The site has long sunlight hours with the mean annual sunshine duration over 3000 h and frost-free period of 150 days. The region has limited water resources with the mean annual precipitation of 164 mm and the mean annual pan evaporation of 2000 mm (measured by a cylinder Class A evaporation pan with a diameter of 120.7 cm and a depth of 25.0 cm). The precipitation at the experiment site during the spring wheat growing season for 2014 and 2015 was 106.8 mm and 118.3 mm, respectively, which was far less than the water requirements of spring wheat. The average groundwater depth is about 30 m.

The soil texture at the experiment site is sandy loam with field water holding capacity of 25.3%. In the 0–90 cm soil layer, the average organic matter, total N, P, K were 6.48 g kg^{-1}, 0.35 g kg^{-1}, 0.51 g kg^{-1} and 15.83 g kg^{-1} respectively, while the available P and K were 9.56 mg kg^{-1} and 124.84 g kg^{-1}, based on our measurements.

2.2. Experimental design and field management

A winter irrigation of 100 mm was conducted in November of previous year to maintain the soil moisture at field capacity level in tillage layer for seed emergence. The spring wheat cultivar yongliang4 was used with a planting density of 375 kg ha^{-1}.

Spring wheat was sown in the experimental field on March 26 and March 21, and harvested on July 24 and July 17 in 2014 and 2015, respectively. The experiment was arranged in a randomized block design with film mulched treatment (M1) and a non-mulched treatment (M0). For M1, it was fully covered with plastic clear film. Each strip was 120 cm wide and 0.008 mm thick, with 2 cm overlap with the adjacent film. Of course, there were holes (e.g., for planting the seeds) and cracks on the film, which normally is less than 5% in area. A total of five irrigation treatments were designed in 2014 and 2015, including W1, W2, W3, W4, W5 (as shown in Table 1). Among them, W1 was regarded as full irrigation, which is based on the custom of local farmers who concern more on high yield than water applied. In recent years however, in order to maximize the value of limited water resources, deficit irrigation, i.e., incomplete supplemental irrigation, was proposed which aimed at obtaining higher crop water productivity with relatively high yield and low irrigation quota. To explore the suitable deficit irrigation strategies, here we also considered 4 deficit irrigation designs in the experiment, i.e., W2 to W5. Compared with W1, W2 cancelled the third irrigation at jointing stage, W3 reduced all irrigation quota to 75%, W4 cancelled the third irrigation and reduced the other irrigation quota to 75% and W5 reduced all irrigation quota to 50%.

The main irrigation methods used in the area are surface irrigation, and the irrigation water mainly comes from groundwater and rivers. Each treatment had two replicates and each plot was 7.5 m long and 5.5 m wide. There was a 1 m wide gap between the plots, also planted with spring wheat. Each plot had a valve and a water flow meter to control the amount of irrigation. Three days before planting, a base fertilizer containing urea (225 kg ha^{-1}), P_2O_5 (450 kg ha^{-1}) was spread evenly over the field and plowed into the soil. Then, the soil surface was covered with film by hand for the M1 treatments. A topdressing fertilizer of urea (150 kg ha^{-1}) was applied to all treatments one day before the first irrigation in both years. The fertilizer entered the soil with irrigation water from the film hole.

Spring wheat was sown in holes of 3 cm diameter and 5 cm deep under the films, with a row spacing of 15 cm and a plant spacing of 10 cm for the two years using a hole sowing machine. Spring wheat was sown with 10–15 seeds in each hole. During each growing season, weeds were removed manually as required.

2.3. Sampling and measurement

2.3.1. Weather data

Precipitation, solar radiation, air temperature, relative humidity and wind speed were obtained at a height of 2.0 m from a standard automatic weather station installed in the experimental station.

2.3.2. Soil temperature

To compare the influence of full/deficit irrigation and the mulching impact on soil temperature, soil temperature recorders (HZ-TJ1, HeZhongBoPu) were installed in the center area of W1M0, W1M1, W5M0 and W5M1 treatment plots, under the plastic film and in the middle of two planting rows. The temperature sensors are placed at soil depths of 10, 20, 40 and 80 cm. The soil temperature close to the ground surface, i.e., at the soil depths less than 10 cm, was not monitored because the sensors would be easily affected by the soil disturbance. The soil temperature was monitored every 60 min and recorded in the memory card during the

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