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Growth, grain yield, and water use efficiency of rain-fed spring hybrid millet (*Setaria italica*) in plastic-mulched and unmulched fields

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ABSTRACT

In order to analyze the effect of plastic mulching on water use efficiency of spring hybrid millet (*Setaria italica*), field experiments were conducted during the 2012 growing season, at an experimental station located in a semi-arid region of North China. Four treatments were applied: (i) plastic mulching of ridges and furrow sowing (T1), (ii) ridges and furrows without plastic mulch (T0), (iii) flat soil with plastic mulch (A1), and (iv) flat soil with no plastic mulch (A0) (control). Dynamics of soil moisture and soil temperature, together with crop growth, were monitored continuously in both mulched and unmulched fields. Changes in water consumption, soil temperature, and plant growth and development were analyzed. Results indicated that plastic mulching produced a 2–5-day advance in emergence of each growth stage. Soil temperature at 0–15 cm depth increased by 1.25 °C and 0.84 °C under mulched treatments A1 and T1, respectively, while soil water content at a depth of 0–10 cm increased by 1.42% and 1.29% in the same treatments. Leaf area index and plant height were also significantly higher in plastic-mulched treatments, except in later growth stages. Because plastic mulching improved tiller and ear numbers significantly, grain yield increased by 13.25% and 6.64%, in Al and T1 treatments, respectively. Water use efficiency at yield levels of plastic-mulched A1 and T1 plots was 24.44% and 3.6% higher than in unmulched flat and furrowed plots, respectively. Plastic mulching significantly reduced water consumption, retained soil water content, and increased soil temperature, to promote spring hybrid millet germination, and increased tiller numbers, and consequently, aboveground dry matter; it eventually significantly improved grain yield and water use efficiency. Plastic film mulching produced greater grain yield, water use efficiency, and benefits when used in flat planting patterns.

1. Introduction

Water shortages are an important factor limiting grain production in many parts of the world (Dong et al., 2011; Shahbaz et al., 2009). In China, a total of 1.33×10^8 hm^2 of land are cultivated, with 59% of these are rain-fed. In rain-fed regions, precipitation is critical for maintaining agricultural production. However, limited and erratic precipitation often results in lower grain yields and sometimes, in total crop failure. Foxtail millet (*Setaria italica L.*) is an important food and fodder crop in semi-arid areas (Xia et al., 2012). The hybrid foxtail millet "Zhangzagu" is popular because of its high drought resistance, yield, and nutritional value (Science Times, 2010). In semi-arid areas, it is desirable to maximize the benefits of the limited rainfall which occurs by increasing water use efficiency (WUE) of millet (Deng et al., 2006; Fang et al., 2010).

Since the beginning of the last century, several new water-saving management practices (such as use of antitranspirants, plastic mulching, and micro-water collecting) have been widely employed in rain-fed areas in China (Berkowitz and Rabin, 1988; Jia et al., 2010; Li et al., 2005; Wang et al., 2011). Mulching with plastic film has been shown to be one of the most efficient methods of improving WUE and grain yield of crops (Han et al., 2004).

Plastic mulching increases topsoil temperature and prolongs reproductive growth, with these aspects positively associated with grain yield (Li et al., 1999; Niu et al., 1998; Qin et al., 2014). When used appropriately, plastic mulching can improve WUE, increase soil temperature for early growth, inhibit weed growth,

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and increase crop yields (Han et al., 2004; Li et al., 2013; Wang et al., 2009, 2012a; Yang et al., 2012; Zhou et al., 2012). However, plastic mulching also has some notable negative effects. Wang et al. (2009) found that plastic mulching restricted potato growth on the North China Plain, mainly because of higher soil temperatures under plastic mulching conditions. Li et al. (2004a) and Tiquia et al. (2002) also showed that plastic mulching decreases potato growth by increasing soil CO_2 content, resulting in poor soil aeration. Li et al. (2001) showed that grain yield and WUE of spring wheat decreased considerably when plastic film mulching was used over the entire growth period, because plastic mulching resulted in insufficient rainfall to support the reproductive growth period. Li et al. (2013) showed that cultivation under ridge and furrow mulching treatments does not significantly alter seasonal evapotranspiration but can regulate water availability during critical growth stages.

Overall, the benefits of plastic mulching outweigh the disadvantages and the practice has proved popular, particularly in fields laid out in ridges and furrows. However, there has been hardly any research regarding plastic mulching treatments applied to the Zhangzagu hybrid millet throughout its growing season. Plastic mulching does not always increase crop yields, which mainly depend on soil types, climatic conditions, crops type, and so on (Gajri et al., 1994), and the present study was mainly focused on wheat, maize and on dual cropping systems. However, little is known about the effect of different plastic film patterns on the growth, yield, and WUE of rain-fed spring hybrid millet, especially in cold areas of China. The aims of this experiment are as follows: (1) to examine the effects of plastic mulching on soil moisture and temperature during the growing season of spring hybrid millet, (2) to ascertain whether plastic mulching can increase hybrid millet yield and WUE in cold areas of China, (3) to compare and analyze the main factors contributing to grain yield and WUE, and (4) to provide a scientific basis for improved rain-fed cultivation of hybrid millet in arid regions in a single cropping system.

2. Material and methods

2.1. Site description

Experiments were conducted at the Xuanhua County Shalingzi Agricultural Experimental Station, Hebei Province, China (115°3′N, 40°63′E). The site is located in a semi-arid region of China and is operated as a single-cropping system. The soil is considered highly suitable for spring maize, spring millet, and potato crops, all of which are important components of food production in China. The mean annual temperature is 7.7 °C. Total annual sunshine hours exceed 2800, and the frost-free period is 110–140 days. The soil is loamy and the top layer (up to 30 cm depth) contains 1.25% total organic matter, with concentrations of rapidly available phosphorous, potassium, and nitrogen being 18.31 mg kg^{-1}, 130.25 mg kg^{-1}, and 42.87 mg kg^{-1}, respectively. Annual mean precipitation is 300–400 mm, of which more than 53% falls in July and August. During the experimental period, rainfall was measured using an automatic weather station (WS-STD1, England) located at the experimental site. Total precipitation during the experimental period was 232.8 mm. Fig. 1 shows daily average air temperature and rainfall distribution over the period of study.

2.2. Experimental design and field management

A hybrid of foxtail millet (*S. italica*), "Zhangzagu 3," was grown at the Xuanhua County Shalingzi Agricultural Experimental Station. Field experiments employed four planting treatments: (1) plastic-mulched ridges and furrow sowing (T1), in which ridges (33 cm wide and 10 cm high) and furrows (5 cm wide) were mulched with plastic film over the entire growing season, (2) ridges and furrows without plastic mulching (T0), in which ridges (33 cm wide and 10 cm high) and furrows (5 cm wide) were left unmulched, (3) flat soil with plastic mulching used during the entire growing season (A1), and (4) flat soil with no plastic mulching, as a control (A0). Transparent polyethylene film, 130 cm wide and 0.008 mm thick, was used for mulching (Shijiazhuang Jintudi Plastic Products General Company, Shijiazhuang, Hebei, China). Each treatment was replicated three times. Each plot was 12 m long and 6 m wide, with a completely randomized arrangement. The approach described below is that of all treatments (Fig. 2a–d).

Millet seeds were sown on May 18, using 15 kg ha^{-1} and row spacing of 33 cm. Crops were harvested on October 1. Before planting, chemical fertilizers containing nitrogen (230 kg ha^{-1}) and phosphorus (160 kg ha^{-1} P_2O_5) were spread evenly and plowed into the soil layer. Workers then shaped the soil into ridges and furrows, as necessary. Half of the ridges and furrows were covered with plastic film for treatment T1. Half of the ridges and furrows were left uncovered for treatment T0. The edges of the plastic film were buried 5 cm deep into the furrows to ensure that the film was tightly placed. Millet seeds were planted by hand in furrows, with one row of seeds per furrow. In the case of treatment A1, seeds were planted in a flat field and mulched with plastic film, with row spacing of 33 cm. For the control treatment (A0), seeds were planted in flat soil with no plastic mulching and with row spacing of 33 cm. None of the plots were irrigated during the growing season. All other management practices were employed consistently across plots.

2.3. Sampling and measurement

2.3.1. Soil temperature

A set of Adcon SM1 soil moisture probes and an A753 addwave Remote Telemetry Unit (RTU) were placed in the middle of a furrow (T1, T0) and in a flat mulched and unmulched field (A1, A0), with four treatments per plot. Soil temperature was recorded every 15 min during the growing season, at soil depths of 15 cm, 45 cm, 75 cm, 115 cm, and 125 cm.

2.3.2. Soil moisture and water use efficiency

Total precipitation and other weather data were collected from a weather station located at the experimental site, from sowing to harvest stages. Soil moisture was measured to a depth of 150 cm at 10 cm intervals, using an Adcon SM1 soil moisture probe, and the RTU recorded soil moisture every 15 min over the growing season. Mean soil moisture was calculated as the mean of three replicates. The gravimetric soil water content was measured accordingly at 10 cm intervals between 0 and 150 cm depth at the time of planting (0 days after sowing, DAS), at jointing (50 DAS) and flowering (80 DAS) stages, and on the date of harvest (130 DAS). For each treatment, soil samples were collected randomly using a soil drill from three locations in the middle of the furrow and from other flat soil areas. Soil cores were weighed wet, then oven-dried at 105 °C for 48 h. Average water content (mm) for the 150 cm soil core was calculated by multiplying the soil volumetric water content by soil profile depth. Total water used was calculated from initial soil water content minus final soil water content, precipitation, runoff, drainage, and capillary rise, using the following equation:

$$ET = P + I + C + \Delta W - R - D \quad (1)$$

where ET is evapotranspiration (mm) over the whole growth period of hybrid millet, P is precipitation (mm), I is irrigation (mm), C is capillary water rise to the root zone (mm), ΔW is soil moisture change (mm) of the soil profile (0–150 cm depth) between planting and harvest periods, R is run off (mm), and D is soil water drainage below the crop root zone (mm). Since there was no irrigation in this