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Straw retention and plastic mulching enhance water use via synergistic regulation of water competition and compensation in wheat-maize intercropping systems

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ABSTRACT

Synergistic regulation of water competition and compensation is critical for the effective use of water in sustainable intercropping systems. A field experiment was conducted on different measures of plastic mulching and straw retention (no-tillage with straw standing in wheat strip and two-year plastic mulching in maize strip, NTSSI2; no-tillage with straw covering in wheat strip and two-year plastic mulching in maize strip, NTSI2; conventional tillage with straw incorporation in wheat strip and annual new plastic mulching in maize strip, TSI; and conventional tillage without straw retention in wheat strip and annual new plastic mulching in maize strip, CTI), which were used in strip intercropping from 2014 to 2016. We determined the effects of integrated measures on coordinating water competition and compensation between inter-strips. The intercropped wheat competed for soil water from the maize strips during the wheat growth period. After wheat harvest, the intercropped maize obtained compensatory soil water from the wheat strips. The results showed that the NTSI2 treatment favorably weakened wheat competition of soil water from the maize strip and strengthened wheat strip compensation of soil water for maize growth compared with CTI treatment. Thus, compared to the CTI treatment, the potential movement amount of soil water in NTSI2 was lowest, decreased by 25.8–58.9% during wheat growth period, but it arrived at the highest, increased by 42.2–60.8% after wheat harvest. The NTSI2 treatment improved grain yield by 13.8–17.1% and enhanced WUE by 12.4–17.2% compared with CTI. The improvement in crop yield and WUE was partly attributed to the coordinated water competition between the inter-strips and the water compensation effect from the early-maturing wheat to the late-maturing maize.

1. Introduction

Global demands for major grains, such as maize and wheat, are projected to improve by 70% by 2050 (Tilman et al., 2011). To achieve this target, grain production must be increased substantially. Given the limited availability of uncultivated land on the planet and the growing environmental problems associated with converting carbon-rich grasslands and forests into cropland (Godfray et al., 2010), the future increases in grain production must be derived primarily from existing farmland (Garnett et al., 2013). In semiarid northwestern China, for example, annual precipitation is less than 200 mm, while annual soil evaporation is greater than 2400 mm (Chai et al., 2014). Historically, agriculture relies on groundwater for irrigation (Chai et al., 2014), but the depth of the water table has declined substantially in recent years due to climate change and over exploitation of groundwater resources (Zhang, 2007). Thus, water shortage is threatening crop production and agricultural sustainability. An added pressure is the severe competition for water resources between the agriculture and rapidly developing urbanization (Kendy et al., 2007; Poumanyvong et al., 2012).

Several innovative water-saving methods, such as straw and plastic film mulching (Yin et al., 2015), regulated deficit irrigation (Chai et al., 2014; Yang et al., 2011), and the enforcement of bylaws and policies in water resource management (Chai et al., 2014), have been used to conserve water in agricultural production. One of the most effective approaches to improve water use efficiency (WUE) in field crop production is strip intercropping. It is a cropping system in which an early-

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sown, cool-season crop is relay-planted with a late-sown, warm-season crop in strips on the same field (Yin et al., 2015). Strip intercropping has been reported to increase crop yields by improving the use of available soil water (Walker and Ogindo, 2003; Yang et al., 2011), nutrients (Hu et al., 2016; Inal et al., 2007), and solar radiation (Awal et al., 2006; Gou et al., 2017), compared with single crops. In particular, the wheat-maize strip intercropping pattern, which was introduced to the oasis irrigation area of northwestern China in the 1970s, is still a prevailing farming pattern (Yin et al., 2015), which has contributed strongly to eliminate poverty and strengthen food security. The strip intercropping system, in combination with regulated deficit irrigation (Yang et al., 2011) or straw and plastic mulching (Yin et al., 2017, 2015), can significantly enhance WUE in semiarid areas of northwestern China, where the temperatures permit only one crop annually (Yin et al., 2016).

However, the mechanism for improved WUE in strip intercropping is poorly understood. A number of studies have shown that the enhanced WUE is due to the increased total crop yield per unit of water supply (Chen et al., 2015; Yang et al., 2009). When two crops are planted together in alternate rows, aboveground interspecies interactions help to improve the canopy structure availability in light capture between the two contrasting crops (Barillot et al., 2011; Munz et al., 2014), also to enhance the light environment, such as transmittance of photosynthetically active radiation (PAR) (Yang et al., 2014). In addition, underground interspecific competition and facilitation may occur simultaneously when two crops are planted together in arid regions with high soil evaporation. Underground interspecies interactions might lead to both competition and complementary use of soil moisture between the intercrops. Furthermore, soil water movement in the rooting zones may occur (Chen et al., 2014; Li et al., 2014; Mu et al., 2013). However, there is a lack of quantitative studies on the soil water that was competed for between two intercrops during their co-growth period and compensated for after the harvest of early-maturing crop. It is unknown whether the two intercrops actually compete for soil water and may provide a compensatory effect by one intercrop to the other. Current knowledge of soil water competition and compensation under efficient agronomic measures of soil water-regulation, such as plastic and straw mulching patterns, is limited. Thus, the basic mechanisms of improvement of grain yield and water use efficiency through the two agronomic measures of intercropping are still unknown.

In this study, we designed two key cooperative and innovative crop production measures: (i) straw retention approaches in wheat strips, and (ii) plastic film mulching patterns in maize strips of wheat-maize strip intercropping. The objectives of this study were to (I) determine the temporal and spatial distributions of soil water under the two neighboring strips, and (II) quantify the soil water competition and compensation between the two intercrops under different straw retention options in combination with plastic mulching. The main hypothesis is that straw retention and plastic mulching improves crop yields and WUE of wheat-maize intercropping through (a) weakening soil water competition of wheat from the maize strip during wheat growth period, and (b) a compensatory effect for soil water movement from early-maturing wheat strip to late-maturing maize strip after wheat harvest. The hypothesis was tested with a 3-year field experiment conducted in an oasis region of Northwestern China.

2. Materials and methods

2.1. Site description

The field experiment was conducted at the Wuwei Experimental Station of Gansu Agricultural University (37°34′ N, 102°94′ E, 1506 m a.s.l.) from 2014 to 2016. Local long-term (1960–2015) annual precipitation is 172 mm and annual potential soil evaporation is greater than 2400 mm. The experimental site has an average annual sunshine of 2945 h, solar radiation of 6000 MJ m^{-2}, and frost-free period of 156 d. Temperature conditions are suitable for intercropping patterns. In 2015 and 2016, the weather conditions were close to the long-term averages, with precipitations of 176.0 and 195.7 mm throughout the growth period of intercrops in 2015 and 2016, respectively. In 2014, however, the precipitation in growing season was 261.6 mm, above the long-term average.

2.2. Experimental design and crop management

The field experiments were conducted with a randomized, complete block design with three replicates for each treatment. A pre-experiment was carried out in 2013 to develop different wheat straw management methods in the field combined with two-year plastic film mulching as preparation for the experiments in 2014, 2015, and 2016. Four different approaches of wheat straw management were designed at wheat harvest in 2013, 2014, and 2015, including (a) no-tillage with 25–30 cm wheat straw standing in the plots (NTSS); (b) no-tillage with 25–30 cm wheat straw covering soil surface (NTS); (c) conventional tillage with a depth greater than 30 cm and with 25–30 cm wheat straw incorporated into soil (TS); and (d) conventional tillage in late fall but all straw removed from the plots, (CT). All approaches were applied to the wheat strips in the wheat-maize intercropping system. The two types of plastic film mulching applied to the maize strips included (a) no tillage with two-year plastic film mulching and (b) conventional tillage with annual new plastic film mulching. Two types of no-tillage (with wheat straw retention and two-year plastic mulching) produced two no-tillage treatments for wheat-maize intercropping, e.g. (i) no-tillage with 25–30 cm straw standing in wheat strip and two-year plastic film mulching in maize strip (NTSSI2) and (ii) no-tillage with 25–30 cm straw covering wheat strip and two-year plastic film mulching in maize strip (NTSI2). Conventional tillage with straw incorporation or without straw retention and annual new plastic film mulching produced two conventional tillage treatments for wheat-maize intercropping, e.g. (i) conventional tillage with 25–30 cm wheat straw incorporated into soil of wheat strip and annual new plastic film mulching in maize strip (TSI) and (ii) conventional tillage without straw retention in wheat strip and annual new plastic film mulching in maize strip (CTI), which was also the regular farming practice (control). Thus, there were a total of 12 experimental plots (4 treatments × 3 replicates). Each experimental plot was about 48 m^2 (10 m × 4.8 m). There was a ridge (0.5 m wide by 0.3 m high) between two neighboring plots to eliminate the potential movement of irrigation water. In late fall of each year, different tillage and residue options were prepared for the wheat strips, while the maize strips with conventional tillage and annual new plastic mulching were deep-plowed. The soil of TSI and CTI treatments was plowed with a depth greater than 30 cm in the previous fall for weed control. In the following spring, soils in wheat strips were fertilized, harrowed, smoothed, and compacted. Then, wheat was planted with a strip rotary tillage wheat seeder. At the same time, a new plastic film was mulched on the surface of maize strips under TSI and CTI treatments. Also, maize was planted with a manual duckbill punch roller dibbler.

In the wheat-maize intercropping systems, wheat and maize were planted alternately in 160-cm wide strips (Fig. 1). In each 160 cm strip, two rows of maize (80 cm strip and 40 cm row spacing) were adjacent to six rows of wheat (80 cm strip and 12 cm row spacing). Each plot had three sets of such strips (160 cm per set × 3 sets = 4.8 m plot width). Spring wheat (*Triticum aestivum* L. cv. *Ning-chun NO. 2*) was planted on 21 March, 29 March, 30 March and harvested on 24 July, 28 July, 21 July in 2014, 2015 and 2016, respectively. Maize (*Zea mays* L. cv. *Xian-yu No. 335*) was planted on 25 April, 24 April, and 20 April and harvested on 1 October, 28 September, and 20 September in the three years, respectively. The planting density was 3,750,000 plants ha^{-1} for wheat and 52,500 plants ha^{-1} for maize. Urea (N fertilizer) and diammonium phosphate (P fertilizer) were broadcast and incorporated into the soil at sowing. The pure N application rates for wheat and maize were 225 and 450 kg ha^{-1}, respectively, while the P application