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Coupling effects of plastic film mulching and urea types on water use efficiency and grain yield of maize in the Loess Plateau, China

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ABSTRACT

Increasing water and nitrogen use efficiency is important for sustainable agricultural development, especially in arid and semi-arid areas. A two-year field experiment was conducted to investigate the effects of field management practices on soil water, maize development, and yield on the Loess Plateau, China. The experiment adopted a split-plot design, with three mulchings as the main-plot treatments and two urea types (225 N ha^{-1}) as the sub-plot treatments. Treatments were established as: (1) no plastic film mulching with urea (NU), (2) no plastic film mulching with controlled release fertilizer (NC), (3) white plastic film mulching with urea (WU), (4) white plastic film mulching with controlled release fertilizer (WC), (5) black plastic film mulching with urea (BU), and (6) black plastic film mulching with controlled release fertilizer (BC). The soil water storage was higher under black plastic film mulching than that under other treatments for most sampling dates within the two experimental years, especially in the second maize growing season. Higher soil water stimulated maize growth, as indicated by a higher plant height, leaf area index, and greater biomass accumulation; thus, the highest grain yield (16.64 t ha^{-1}) and water use efficiency (28.3 kg ha^{-1} mm^{-1}) in 2014 was recorded in BC plots, which were higher by 34.5% and 34.8%, respectively, compared with those in NU. White plastic film mulching also increased the soil water content and promoted maize development, grain yield, and water use efficiency; thus, higher grain yield (16.02 t ha^{-1}) and water use efficiency (26.5 kg ha^{-1} mm^{-1}) were recorded in WC plots in 2014. In the two experimental years, controlled release urea treatments always produced significantly higher maize yields than conventional urea treatments, except the NC plots in 2013. However, significant soil water depletion in the deeper (>120 cm) soil layers was detected at harvest time in 2014 under BC treatment, indicating that higher yields might not be sustained in long time periods. In conclusion, plastic film mulching, particularly black plastic film mulching combined with controlled released fertilizer, could improve the water use efficiency and suitably meet the nitrogen requirements of maize, thereby increasing the grain yield in the Loess Plateau, China.

1. Introduction

Water stress is the major limiting factor for crop production in rain-fed farming systems in arid and semi-arid areas (Debaeke and Aboudrare, 2004). In China, most rain-fed farming systems are located in the semi-arid Loess Plateau, accounting for about 25 Mha (Deng et al., 2006; Zhang et al., 2014). The climate in the region is mostly semi-arid with high evaporation and annual precipitation ranging from 200 mm to 600 mm (Li and Xiao, 1992), but declining trends have been revealed from 1961 to 2010 in Changwu Experimental Area in the Loess Plateau, China (Fig. 1). Thus, the water shortage issue is expected to worsen in the future. Dryland farming in the Loess Plateau is dominated by monoculture cropping systems (Zhang et al., 2011), mainly spring maize (*Zea mays L.*), winter wheat (*Triticum aestivum L.*), and spring potato (*Solanum tuberosum L.*).

Technologies that improve crop water use efficiency (WUE) are critical for sustainable crop production and local food security (Shan and Chen, 1993; Turner, 2004; Zhang et al., 2014; Zhao et al., 2014). Many management strategies have been tested to improve rainwater use efficiency in semi-arid regions over the past decades (Beltrano et al., 1999; Boers and Ben-Asher, 1982; Xiao and Wang, 2003), such as rainwater harvesting (Mzirai and Tumbo, 2010; Zhao et al., 1995), mulching including plastic, crop straw, and gravel-sand cover (Sarolia and Bhardwaj, 2012; Wang et al., 2011b), and drip or supplement irrigation (Anita and Giovanni, 2012; Lamont et al., 2003; Wang et al., 2011a; Zhao et al., 2014). These practices have become popular to a great extent. As one of the most

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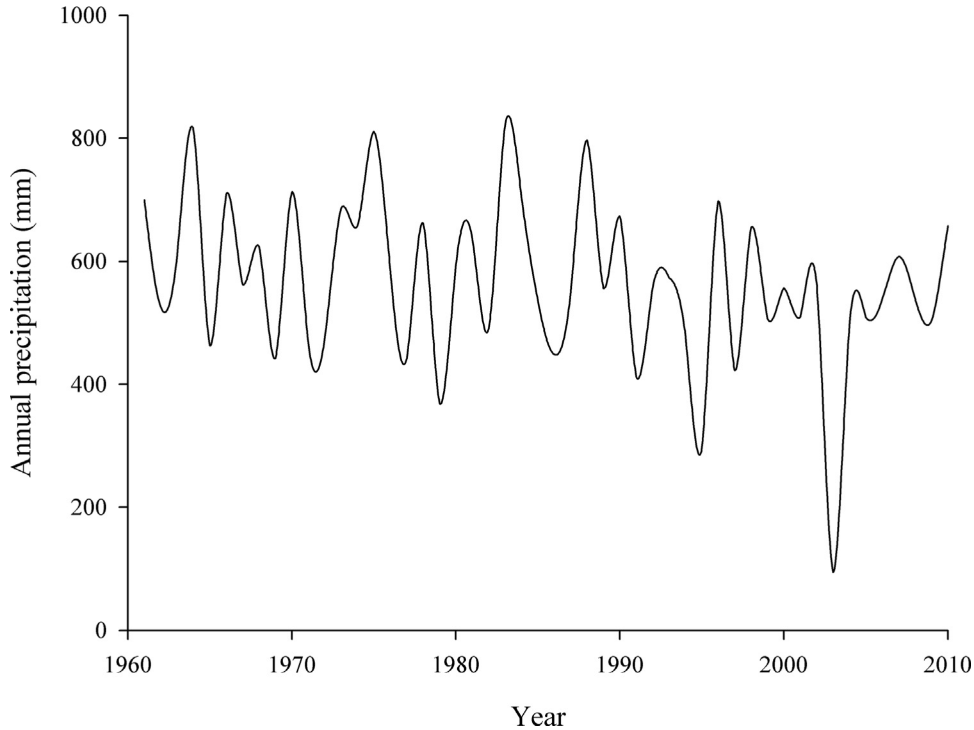

Fig. 1. Annual precipitation from 1961 to 2010 in a site in the Loess Plateau of China.

effective measures, plastic film mulching can improve WUE and grain yields for rain-fed regions (Gan et al., 2013). It has mainly been used in maize (Zegada-Lizarazu and Berliner, 2011), wheat (Li et al., 2004), cotton (Zhou et al., 2012), and potato (Kar, 2003; Wang et al., 2008; Zhao et al., 2012).

Studies have confirmed that plastic film mulching decreases the amount of water loss caused by evaporation (Li et al., 2013b; Liakatas et al., 1986; Wang et al., 2008), enhances soil water infiltration (Gan et al., 2013), improves crop yields both in quantity or quality (Kar, 2003; Li et al., 2004; Luis et al., 2011; Ramakrishna et al., 2006; Wang et al., 2008), and increases WUE (Wang et al., 2008; Zegada-Lizarazu and Berliner, 2011). In addition, it is effective in enhancing topsoil temperature in the early growing season when temperatures are low in spring (Gan et al., 2013). This effect gradually diminishes with plant development for some crops, especially potato (Wang et al., 2005; Zhao et al., 2012). However, other studies showed that plastic film mulching for the whole growth duration can considerably lower yields because of consistently higher temperatures in midsummer, and the plants easily suffer from heat stress (Li et al., 2004; Zhao et al., 2012; Zhao et al., 2014). Therefore, some measures must be applied, including mulching soil surface with crop straw (Chakraborty et al., 2008), covering plastic film with the soil (Fan et al., 2012), removing the mulch (Zhao et al., 2012), or using colored plastic film, such as black film.

Crop yields have increased significantly with the increasing use of nitrogen (N) fertilizer (Hu et al., 2013; Kirda et al., 2005; Zand-Parsa et al., 2006). However, excessive use of N fertilizer not only causes a huge waste of resources and economic losses, but also adversely impacts the environment (Godfray et al., 2010), thereby affecting the safety of human beings (Hvistendahl, 2010; Schindler and Hecky, 2009). Researchers have indicated that controlled release urea, compared with conventional fertilizer as urea, can not only significantly improve crop yields and nitrogen use rate, but also reduce the adverse effects of conventional fertilizer on the soil, providing better protection for the environment and human beings (Hu et al., 2013; Shaviv and Mikkelsen, 1993; Shoji, 2005).

Controlled release fertilizers (CRFs) have been defined as products that control the released time and quantity of nutrients in fertilizers to maintain consistency for each growth period with fertilizer supply, as well as minimize the potential of nutrient losses to the environment, compared with "reference soluble" fertilizers (Snyder et al., 2009; Wang et al., 2009a,b). The extended period of continued availability of slow and CRFs may occur through various mechanisms. These mechanisms include controlled water solubility of the material by semi-permeable coatings, occlusion, or inherent water insolubility of polymers, natural nitrogenous organics, protein materials, or other chemical forms (Snyder et al., 2009). Studies showed that CRFs can increase maize yield (Yi et al., 2008; Zhu et al., 2003). However, CRFs are more expensive than conventional fertilizers, and nutrient release may be difficult to predict; moreover, some coating materials can even harm the environment (Azeem et al., 2014). Most CRFs focus on regulating N release without considering other indispensable nutrients, such as phosphorus (P) and potassium (K), which may not meet the requirements of plants for multiple nutrients (Zhao et al., 2010). All these shortages limit the application of CRFs on field crops (Yan et al., 2008). Inexpensive, easily fabricated, and environmentally friendly CRFs are urgently needed in crop production.

Previous studies on plastic film mulching mainly focused on white plastic film mulching, and only a few on black plastic film mulching have been conducted. Hence, information on the coupling effect of black plastic film mulching and controlled release urea is limited. The mechanisms underlying the improvement in WUE and crop yield because of this coupling effect remain unknown. In this study, a field experiment was conducted to examine the interaction effects of varying plastic film mulching treatments with urea types on maize growth and soil water. This field study aimed to (1) investigate the coupling influence of varying plastic film mulching treatments and urea types on shoot height, leaf area index (LAI), and total aboveground biomass of spring maize; (2) assess the coupling impacts of varying plastic film mulching treatments and urea types on soil water storage,