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Effects of the ridge mulched system on soil water and inorganic nitrogen distribution in the Loess Plateau of China

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ABSTRACT

The semi-arid region of the Loess Plateau is typical of rain-fed agricultural production in Northwestern China. In this area, the ridge mulched system (RM) is a widely-used measure to increase crop yield. The purpose of this study was to investigate the effect of RM on soil water and inorganic nitrogen (N) distribution, and grain yield of maize (*Zea mays* L.). The study was conducted over three consecutive years and consisted of four treatments (each replicated three times): i) RM with N application rate of 260 kg N ha^{-1} (RM-N260); ii) RM with 180 kg N ha^{-1} (RM-N180); iii) a traditional flat cultivation system without mulching (F) with 260 kg N ha^{-1} (F-N260); iv) F with 180 kg N ha^{-1} (F-N180). Mean soil water content during the maize growing season was increased by RM in 2013 only. However, RM increased the soil water storage significantly at the 3-leaf (V3) and 6-leaf stage (V6), and decreased evapotranspiration (ET) during pre-silking stage in all years. Compared to F, RM significantly improved maize grain yield by 79–123% in 2013, 23–25% in 2014, and 11–12% in 2015. Following three years of maize cultivation, soil inorganic N content increased substantially (two- to three-fold) in the RM system and 60% of the total inorganic N was accumulated in the top soil layers (0–60 cm) under the mulched ridge. Relative changes were much smaller in F, and most of inorganic N was stored in 0–20 cm and 100–160 cm soil layers. Generally, RM resulted in higher soil water storage during the pre-silking stage, which was the main reason for the improved maize grain yield. The nitrate leaching risk was reduced in RM-N180 compared with F, but nitrate leaching from the furrows between ridges was observed in RM-N260. However, the large increase in soil inorganic N content in RM-N180 after three years' cultivation indicates an oversupply of N and a potential risk of N losses to the environment over the longer term. Our study indicates, therefore, that RM is a suitable system for maize cropping in the semi-arid region of the Loess Plateau, with benefits in water and N use efficiency, but recommendations for appropriate N application rates are required to ensure long term agricultural sustainability, accounting for grain yields and environmental impacts. The mechanisms for inorganic N accumulation under the RM system are not fully understood and warrant further investigation.

1. Introduction

Plastic film mulching has developed rapidly following it's introduction to China in 1978 and is now widely applied in crop production in arid and semiarid regions (Dong et al., 2009; Li et al., 2004). Several mulching systems have been used in recent years, including 1) fully mulched ridge and furrow system: two ridges and furrow fully mulched with plastic film (Zhou et al., 2009); 2) ridge mulched system: alternating ridge and furrow with plastic film mulched-ridge (Liu et al., 1989); 3) flat half mulched system: alternating mulched row and bare row in flat cultivation (Liu et al., 1989); and 4) flat fully mulched system: flat plot all mulched with plastic film (Liu et al., 1989). Of these, the ridge mulched system has been most widely adopted, leading significant increases in crop yield rain-fed agricultural areas of Chinese Loess Plateau, especially in areas with 400–600 mm annual precipitation (Jiang et al., 2016; Wang et al., 2015; Wang et al., 2016). The yield increases under plastic film mulching have been attributed to factors including: 1) reduction in soil evaporation and increase in crop transpiration; 2) increase in water harvesting; 3) increase in soil temperature; and 4) increase in activation of soil nutrients (Zhou et al., 2009; Zhao et al., 2002; Zhou, 1996). These factors change the soil environment, improving conditions for crop growth, resulting in higher water

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use efficiency and nutrient availability.

Water is the most limiting factor for crop production under rain-fed agriculture in arid and semiarid areas. However, studies have shown that the temporally irregular rainfall distribution and inefficient management of rainwater, rather than total rainfall amount, are the primary limits for crop production (Barron et al., 2003; Zhu et al., 2015). Zhu et al. (2015) indicated that plastic film mulching improved rainwater management to overcome water limitations during dry spells, which promoted crop growth and increased yields significantly. Drought and mild chilling stress often occur in the Loess Plateau of China, especially during the early stage of the maize growing season; plastic film mulching can improve the soil water content and temperature during this stage resulting in increased yield (Jiang et al., 2016; Zhang et al., 2014). The main crops (i.e. spring maize and winter wheat) on the Loess Plateau are conventionally cultivated as a single crop per year followed by several months of bare fallow. It is generally assumed that water stored in the soil during fallow period is utilized by the subsequent crop. The antecedent soil moisture content (prior to sowing) may also cause or mitigate water stress during the early stages of crop growth. However, few studies have considered the interactions between plastic film mulching and antecedent soil moisture content on crop yield.

Fertilization can increase crop yield and enhance drought resistance of crops in arid and semiarid regions (Liu et al., 2013). However, excessive application of N fertilizer results in low N use efficiency and high N losses with environmental impacts including greenhouse gas emission, water contamination, soil quality degradation, and soil nitrate accumulation in deep soil layers (Davidson 2009; Morell et al., 2011; Reay et al., 2012; Zhou et al., 2016). Plastic film mulching not only results in improved soil physical properties (soil water and temperature) but also directly changes soil biological characteristics and soil fertility (Liu et al., 2013). Soil inorganic nitrogen (N) is an important indicator for soil fertility and productivity. Since the plastic film mulching changes the soil microenvironment with associated changes to the N cycle processes, the soil inorganic N distribution under plastic film mulching systems may differ to that under traditional cultivation. Plastic film mulching may increase soil microbial activity due to the improved soil water and temperature conditions and thereby enhance mineralization (Wang et al., 2006). High inorganic N contents have been observed in soil profiles under plastic film mulching, especially in topsoils, and enhanced soil mineralization could be one reason (Wang et al., 2006). Another reason may be related to reduced N leaching under plastic film mulching (Ruidisch et al., 2013; Liu et al., 2017a,b). However, Liu et al. (2014a,b) found that the nitrate accumulation was more related to N fertilizer application rates. High N input resulted in higher nitrate accumulation in the soil profile, which may also increase N leaching and greenhouse gas emissions (Kettering et al., 2013; He et al., 2018; Anikwe et al., 2007). Several studies have investigated the fate of N under plastic film mulching, however, few have considered the potential differences that may occur between the ridge and furrow under a ridge mulched system in arid and semiarid areas (Liu et al., 2015; Wang et al., 2016; Kettering et al., 2013). Ridge mulched systems have a mulched ridge and furrows without mulch, thus the N transformations and transport processes could be different. A study conducted under a monsoon climate showed that N leaching mainly occurred from the furrow in a ridge mulched system (Kettering et al., 2013). However, the vertical distribution and temporal patterns of soil inorganic N under ridge mulched systems are not well understood in rain-fed drylands.

Many studies have investigated the relationship between soil water content and crop yield to clarify the yield increase mechanism under plastic film mulching, however, very few have considered the impacts of the effects on water content and soil inorganic N distribution on both food security and sustainable agriculture. This study focused on a ridge mulched system in a maize crop on the Loess Plateau of China, taking crop production and environmental sustainability into consideration. The objectives were to 1) evaluate the effect of the ridge mulched system on soil water content, soil water storage, and water use efficiency; and 2) investigate soil inorganic N pools and distribution, considering the ridge and furrow as different units.

2. Material and methods

2.1. Site description

The field experiments were conducted from 2013 to 2015 at the Changwu Agricultural and Ecological Experimental Station, located on the Loess Plateau of China (35.28°N, 107.88°E, ca. 1200 m above sea level). The annual mean air temperature is 9.2 °C and average annual rainfall is 582 mm, 73% of which occurs during the maize-growing season. The groundwater table is approximately 80 m below the surface. The cropping system in this area is one crop of maize or wheat per year. According to Chinese Soil Taxonomy, the soils are Heilutu, belonging to Cumuli-Ustic Isohumosols (light silt loam) (Gong et al., 2007). The soil properties in the top 20 cm are as follows: bulk density, 1.3 g cm^{-3}; pH, 8.4; soil organic carbon content, 9.5 g kg^{-1}; total N content, 1.05 g kg^{-1}; available phosphorus (Olsen-P) content, 20.7 mg kg^{-1}; available potassium (NH_4OAc-K) content, 133.1 mg kg^{-1}; and mineral N content, 28.8 mg kg^{-1}.

2.2. Field experiments

This study included a ridge mulched system (RM) and a traditional cultivation system (i.e. flat cultivation without mulching) (F) over three maize-growing seasons (Fig. 1). There were two fertilizer application treatments: 180 kg N ha^{-1}, as recommended for traditional cultivation; 260 kg N ha^{-1} as per local farmer practice, giving a total of four treatments (RM-N180, F-N180, RM-N260, and F-N260). Plots were established a 5 × 10 m in a randomized block design with three replicate plots per treatment. Urea (N 46%) was used as N fertilizer in all

Fig. 1. Maize cultivation systems used in the study. Left picture shows the ridge mulched system (RM) (RM-R: ridge in ridge mulched system; RM-F: furrow in ridge mulched system); right picture shows the flat cultivation system (F).