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Effects of tillage, mulching and N management on yield, water productivity, N uptake and residual soil nitrate in a long-term wheat-summer maize cropping system

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ABSTRACT

A thorough understanding of coupled effects of soil management (tillage), mulch and N rate on the wheat-maize system is crucial for achieving sustainable agriculture in the southern Loess Plateau of China. This study was based on a 12-year (2003–2015) field experiment and aimed to evaluate the impact of three wheat-maize systems (S) which varied in terms of tillage, mulch, wheat row spacing and irrigation management (CT, conventional tillage with no mulch; RFM, ridge-furrow with plastic film-mulched ridges and straw-mulched furrows; CTM, conventional tillage with straw mulch) combined with N fertilizer rates (0, 120 and 240 kg N ha^{-1}) on crop yield, water productivity (WP, kg grain per kg of water input), N uptake, residual soil nitrate (RSN) and soil physicochemical properties. Results demonstrated that RFM significantly increased maize yield in comparison with CT in all 12 years, while CTM increased yield in comparison with CT from year 3 onwards. By contrast, wheat yield was not strongly influenced by RFM and CTM from 2004 to 2012 (except for 2008). Maize yields of RFM were significantly higher than those of CTM from the third year onwards. Compared with CT, the other two practices, and more so RFM, showed beneficial effects on crop yield, the amount of stored water, WP, N uptake and RSN. N fertilization significantly increased crop yield, WP and N uptake, while no significant difference was observed between the N120 and N240 treatments. Notably, considerable buildup of RSN to ~ 490 kg N ha^{-1} at maize harvest and ~340 kg N ha^{-1} at wheat harvest were observed in 0–200 cm soil depth when 240 kg N ha^{-1} was applied. These results suggest that the conventional N rate of 240 kg N ha^{-1} is excessive, and risks serious contamination of the groundwater as a result of NO_3^--N leaching. The N120 treatment was characterized with considerably lower RSN accumulation after harvest, while maintaining crop yield. Thus, we concluded that the RFM practice with 120 kg N ha^{-1} application could reduce irrigation water and fertilizer inputs and increase crop land and water productivity, and is a promising strategy for developing sustainable agriculture in the southern Loess Plateau and other areas with similar climate and cropping systems.

1. Introduction

The winter wheat-summer maize rotation system has been widely adopted in the southern Loess Plateau of northwest China (Deng et al., 2006). Crop production in this region is primarily constrained by water shortage and nutrient deficiency (Li et al., 2015). Uneven rainfall and high evaporation always result in an imbalance between crop water requirements and water supply thus leading to low grain yields (Gan et al., 2013). The limited annual precipitation is insufficient to support two crops and therefore supplemental irrigation is usually applied to wheat during spring and occasionally to maize if rainfall is scarce during early growth stage (Deng et al., 2006). Climate change predictions suggest that the Loess Plateau will become drier and warmer in the future (Sun and Ma, 2015). Agricultural irrigation water resource depletion is becoming increasingly severe with the growing population and global climate change (Elliott et al., 2014). Thus, conserving and efficiently utilizing the limited precipitation available is crucial for cropping in the Loess Plateau and other water-limited areas in the world.

Numerous studies have demonstrated that soil surface mulch with crop straw or plastic sheets is an effective means of increasing maize or/and wheat yield and water productivity (WP, kg grain per kg of water input) in the Loess Plateau (Liu et al., 2014; Li et al., 2015; Zhang et al., 2015). Similar beneficial results were also observed in Mexico

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(Govaerts et al., 2006; Verhulst et al., 2011), India (Sharma et al., 2011; Lenka et al., 2013; Balwinder-Singh et al., 2016), and other regions of China such as North China Plain (Huang et al., 2015). Moreover, the findings of studies on crop yields in response to straw mulch are still contradictory, including positive (Sharma et al., 2011; Liu et al., 2014; Zhang et al., 2015), or no obvious (Govaerts et al., 2006; Huang et al., 2015) or negative effects (Fabrizzi et al., 2005; Gao et al., 2009; Naveen-Gupta et al., 2016), even though these experiments were treated with a similar amount of straw (~ 4500 kg ha^{-1}). Most of those studies were short-term (1- or 2-year) studies, whereas long-term studies are needed to understand the effects of climate variability and changes in soil properties over time as a result of the different treatments. Therefore, long-term field experiments are needed to clarify the response of grain yield to straw mulch and soil management under a wheat-maize cropping system. Ridge-furrow with plastic film or straw mulching system is widely applied in northwest China (Li et al., 2015), Mexico (Verhulst et al., 2011) and India (Sharma et al., 2011). However, the long-term effects of this management practice are still poorly understood (Li et al., 2017; Zhang et al., 2017), and little information is available regarding a comparison of straw mulch and ridge-furrow with plastic film or straw mulching system influencing the wheat-maize rotation system in water-limited areas.

Nitrogen (N) deficiency is widespread in soils of the Loess Plateau (Guo et al., 2012), and the crop yield gap in this region is greater than 50% due to the limited supply of water and nitrogen (Mueller et al., 2012). During the past two decades, N fertilizer application has increased drastically in pursuit of higher grain yields, and the excessive N fertilization problem has become serious in the wheat-maize rotation system in northwestern China (Zhang et al., 2015). Previous studies documented that the high N application beyond the needs of maize-wheat cropping system would reduce N use efficiency and enhance soil nitrate buildup, and agricultural N management remains a key environmental challenge (Lenka et al., 2013; Yang et al., 2017). Nitrate-N leakage generally occurred when substantial rain or irrigation occur shortly after N application (Jia et al., 2014). In view of the scarcity of irrigation and precipitation, nitrate leaching in cultivated lands of northwestern China has been underestimated or even ignored for many years (Dai et al., 2016). A survey conducted in the Shaanxi province showed that up to 25% of 167 groundwater samples exceeded the WHO drinking water standard (NO_3^--N < 10 mg kg^{-1}) in 1998, and up to 54% of 225 groundwater samples exceeded the critical value of 10 mg kg^{-1} in 2008 (Deng et al., 2008), indicating an increasing risk on the environment. Undoubtedly, these enhanced concentrations of nitrate in the groundwater were associated with the high application of N fertilizer in cultivated lands (Yang et al., 2017). Huang et al. (2015) found that straw mulch could decrease NO_3^--N leaching losses while sustaining maize-wheat grain yields in North China Plain. Murphy et al. (2016) also reported positive effect in southern Mexico. Similarly, several studies have been conducted in the Loess Plateau for optimizing N management, however they were either treated without mulching practice (Zhang et al., 2015; Dai et al., 2016) or performed on monoculture cropping systems (Liu et al., 2014; Li et al., 2015). Up to now, an appropriate N management under the systems involving different combinations of tillage, mulch and irrigation management in order to increase crop yield and decrease the yield gaps remains poorly investigated in wheat-maize cropping systems in the Loess Plateau and other water-limited areas.

In addition, previous related studies mainly focused on crop yield and WP in response to either mulching or N rate, while little attention has been paid on evaluating soil fertility changes such as soil physicochemical properties (Gao et al., 2009; Verhulst et al., 2011; Sharma et al., 2011; Lenka et al., 2013; Bu et al., 2013; Li et al., 2015; Dai et al., 2016; Yang et al., 2017). A comprehensive evaluation of long-term coupled effects of tillage-mulch-irrigation management and N fertilization on wheat-maize cropping systems in the Loess Plateau remains scarce. Therefore, the present study utilized a long-term field experiment initiated in 2003 and aimed to (*i*) examine the combined effects of tillage-mulch-irrigation management and N rate on crop yield, WP, N uptake, and residual soil nitrate; and (*ii*) investigate the changes in soil physicochemical properties under the systems involving different tillage-mulch-irrigation management and fertilizer N application. The information obtained can be used to optimize N management and enhance crop production for the winter wheat-summer maize rotation system in dry sub-humid areas of northwestern China and other areas with similar climates and cropping systems.

2. Methods and materials

2.1. Site description

The field experiment was conducted at the Agricultural Research Station of Northwest Agriculture & Forestry University (34°18′ N, 108°04′ E, and 520 m above the sea level) in Yangling, Shaanxi, China. The site is located in the southern Loess Plateau. A temperate and dry sub-humid climate prevails in this region and the mean annual temperature and precipitation are 12.9 °C and 583, respectively (1957–2015). About 65% of the precipitation occurs between June and September, and the potential evaporation is 1400 mm. The precipitation during the experimental years (2003–2015) is shown in Fig. 1.

The winter wheat and summer maize rotation system is the major local cropping sequence, with rotary tillage for wheat and no-till for maize. Summer maize is usually sown in early June and harvested in early October, and winter wheat is sown in early or mid October and harvested in early June of the following year. The soil at the experimental site is classified as a calcareous Eum-Orthic Anthrosol (Udic Haplustalf in the USDA system), which is the typical soil in the area. Selected chemical properties of the 0–20 cm soil layer at the experimental site in 2003 were as follows: pH 8.25, 15.2 g kg^{-1} organic matter, 0.91 g kg^{-1} total N, and available N, P and K concentrations were 32.3 mg kg^{-1}, 17.2 mg kg^{-1} and 169 mg kg^{-1}, respectively.

2.2. Experimental design

The long-term field experiment was established in 2003 and is still on-going with a maize-wheat rotation. Three tillage-mulch systems have been widely adopted in the study area, and these three systems were compared in main plots in this experiment: CT (conventional tillage with no mulch), RFM (ridge-furrow with plastic film-mulched ridges and straw-mulched furrows), and CTM (conventional tillage with straw mulch). Three fertilizer N rates were compared in sub-plots: 0 (control), 120 (moderate), and 240 kg N ha^{-1} (high; conventional N

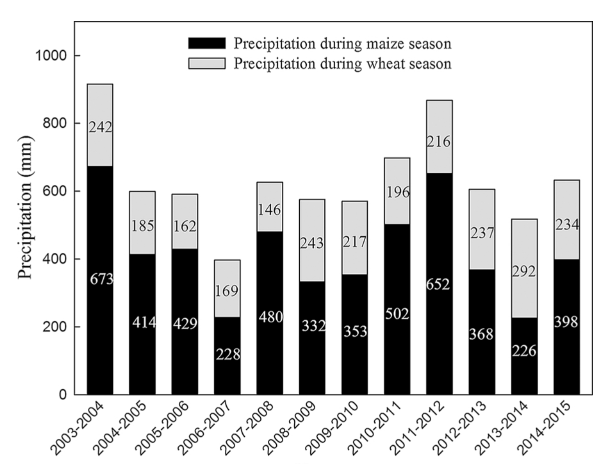

Fig. 1. Precipitation during the 12 consecutive maize-wheat rotation cycles (2003–2015). “2003–2004” represents summer maize in 2003 (from June to September) and winter wheat in 2004 (from October in 2003 to May in 2004), and so on.