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Changes in soil characteristics and maize yield under straw returning system in dryland farming

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ABSTRACT

Inappropriate fertilization has negative effects on soil quality and utilization of soil water storage. The effects of maize straw incorporation at low (LS 4500 kg ha^{-1}), medium (MS 9000 kg ha^{-1}), and high (HS 13,500 kg ha^{-1}) rates combined with chemical fertilizers on soil properties, maize yield and water-use efficiency (WUE) compared with chemical fertilizers (CK) were researched over 5 years under semi-humic conditions in dark loessial soil. The duration of decreased soil bulk density after straw incorporation depended on the straw incorporation rate; compared with CK, only HS treatment significantly decreased soil bulk density from the fourth year of the experiment and onward. Annual straw incorporation had cumulative effects on the build-up of soil enzyme activity. Soil fertility and enzyme activities were significantly improved with increasing straw incorporation rate over time. Straw incorporation rate decided the duration of increased crop yield and WUE; compared with CK, MS and HS treatments had 8.0–39.5% higher maize yield and 6.2–36.8% higher WUE in the five experimental years, whereas LS treatment significantly increased maize yield after the second fertilization year and significantly enhanced WUE after the fifth fertilization year. After the fourth fertilization year, MS treatment had no significant difference with HS treatment on maize yield and WUE. The rational straw incorporation treatment is MS in terms of improving dryland soil fertility, crop product and WUE.

1. Introduction

Soil moisture and nutrients are the primary factors limiting agricultural productivity. The Loess Plateau region of northwest China is a vast semi-arid region characterized by a 300–600 mm annual precipitation (Li and Xiao, 1992), uneven rainfall distribution (with 60–70% falling in July–September), and high rates of soil water evaporation (Li et al., 2000). More than 90% of the farmland in the region is non-irrigated. Maize is the second main crop in the Loess Plateau, cultivated per year with chemical fertilizers. After maize harvest, the farmland is fallowed for approximately seven months. In the fallow period water is conserved in the soil and employed by the subsequent maize. However, reduced organic matter input, tillage, use of monocultures etc. have deteriorated soil physical and hydraulic properties, decreased soil organic carbon and finally influenced the maize yield (Malhi et al., 2003; Fan et al., 2005; Zhang et al., 2009). In addition, conserving the soil water only in the fallow period leads to lower fallow efficiency (soil conserved water per unit of rainfall in the fallow period) (Shangguan et al., 2002) and the decrease of water infiltration depth with higher fertilization (Huang et al., 2002). Thus, the conventional management practices commonly used throughout the Loess Plateau are not likely to be sustainable over the long term.

In order to improve agricultural productivity in the Loess Plateau, there is a need to improve water-use efficiency, soil physicochemical and biological properties (Singh et al., 2007a,b; Monaco et al., 2008; Soon and Lupwayi, 2012). Maize straw has rich nutrient elements of nitrogen, phosphorus and potassium et al. (Xie et al., 2014), so maize straw incorporated into soil influences soil fertility, and then finally affects crop yield. Returning crop straw to the field is one of the important practices of all farming practices to improve crop yield, soil properties and water-use efficiency (ratio of grain yield to seasonal evapotranspiration). Dong et al. (2012) reported that long-term straw application increased soil organic carbon in the red soil area of southern China. Maize straw incorporation increased the soil organic carbon, available nitrogen and available phosphorus levels in 0–40 cm soil layers, and enhanced urease, phosphatase and invertase activities levels

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in 0–60 cm soil layers (Zhang et al., 2016). Return of maize straw resulted in an increase in potential soil respiration (Monaco et al., 2008) and maize yield (Zhang et al., 2009). Long-term additions of straw combined with N annually and P every second year could improve soil water-holding capacity and keep higher soil water content in the conditions of soil moisture stress (Fan et al., 2005).

However, inappropriate straw application has negative effects on soil environment and crop productivity. Decomposition of straw incorporated into soil consumes soil available nitrogen. Therefore, higher rate of straw incorporation consumes more soil available nitrogen, which resulted in lower soil available nitrogen used for crop growth and then finally influenced crop growth. Wang et al. (2009) found that 13,500 kg ha^{-1} straw incorporation without chemical fertilizers decreased maize yield.

Hence, there is a need to identify appropriate straw incorporation rates that will improve soil quality, water use efficiency and maize yield. This research was to investigate the effects of three rates of straw application combined with the same inorganic fertilizer on maize yield, water-use efficiency and soil properties.

2. Material and methods

2.1. Site description

The study was conducted with maize on anthroposols soil (sand 26.8%, silt 41.9%, and clay 31.3%) in the years 2007–2011 at Ganjing, Heyang, Shaanxi China (35°24′N, 110°17′E; 850 m altitude). The mean annual rainfall is 571.9 mm and the mean annual evaporation is 1832.8 mm at the site. For the rainfall volume information at the different growth periods of maize, see Table 1.

2.2. Experimental design

The field experiment used a completely randomized block design with four treatments, three replicates, and a 4 × 6 m plot. The four treatments were as follows: (i) application of chemical fertilizers only (CK); (ii) returning 4500 kg ha^{-1} maize straw into soil combined with chemical fertilizers (LS); (iii) returning 9000 kg ha^{-1} maize straw into soil combined with chemical fertilizers (MS); (iv) returning 13500 kg ha^{-1} maize straw into soil combined with chemical fertilizers (HS). Urea and diammonium phosphate were used. The chemical fertilizers had 255 kg ha^{-1} N and 90 kg ha^{-1} P. The 102 kg ha^{-1} N and 90 kg ha^{-1} P fertilizers were used before planting the maize. The 153 kg ha^{-1} N fertilizer was used in late July. Maize straw was chopped and incorporated into the approximately 0–25 cm soil depth. The maize straw was applied annually after maize was harvested. The maize variety used was Shendan 16. Maize with 49,500 plants ha^{-1} was sown in mid-April and harvested in mid-September yearly. There was no irrigation over the study years.

Table 1
The rainfall at the different growth period of maize growth in the year of 2007–2011.

Years	Rainfall (mm)					
	Sowing-five leaf collar stage	Five-ten leaf collar stage	Ten leaf collar-tasseling stage	Tasseling-grain filling stage	Grain filling-maturity stage	Whole growth stage
2007	19.9	71.9	27.0	182.3	97.2	398.3
2008	57.7	96.9	27.0	123.4	45.8	350.8
2009	71.5	111.8	46.6	30.9	118.3	379.1
2010	75.9	37.2	92.4	114.0	102.8	422.3
2011	42.2	15.6	52.2	107.5	123.5	341.0

2.3. Sampling and analysis methods

Soil samples were collected from each plot in 0–20 cm soil layer after the maize harvest annually. Four points were used to collect soil samples and then mixed in each plot. The mixed sample was quartered by leaving about 500 g soil sub-sample for analysis. A 1:5 soil/water extract was used for soil pH determiation. The urease and alkaline phosphatase activities were determined according to Tabatabai (1994). Soil organic carbon was determined using the dichromate oxidation method (Walkley and Black, 1934), available nitrogen by micro-Kjeldahl digestion, available nitrogen by the method described by Cornfield (1960), available phosphorus using the method provided by Olsen et al. (1954). Soil bulk density was measured with the core method (Ferraro and Ghersa, 2007) after maize harvest at 0–20 cm soil profile. Twenty plants of maize was harvested in the center of each plot.

Soil moisture was determined gravimetrically by oven (drying method, w/w) in 0–200 cm soil profile before sowing and harvesting of maize.

The following equation was used to calculate soil water storage:

$$W = dbp\% \times 10 \quad (1)$$

Where W (mm) is soil water content; d (cm), soil depth; b (g cm^{-3}), soil bulk density, and p%, the percentage of soil water content in weight. The soil water storage for calculating evapotranspiration was calculated at 0–200 cm soil profile.

The following equation was used to calculate evapotranspiration (ET, mm):

$$ET = P - D - R - \Delta S - Ei \quad (2)$$

Where ET (mm) is the evapotranspiration, P (mm) is the precipitation, D (mm) the downward drainage out of the root-zone where the crop root spread, R (mm) the surface runoff, ΔS (mm) the change in soil water storage, and Ei (mm) is evaporation from intercepted rainfall. In this study D was ignored because the groundwater contribution from a water table 50 m below the surface, and drainage out of the root-zone need not be considered in this area (Wang et al., 2009). Surface runoff was zero because the topography was flat, and Ei was neglected because it was quite constant and constituted a very small proportion of the water balance compared with the other terms (Zhang et al., 2007). ΔS can be either positive or negative. Therefore, evapotranspiration was calculated by precipitation and the change in soil water storage as

$$ET = P - \Delta S \quad (3)$$

The following equation was used to calculate water-use efficiency:

$$WUE = Y/ET \quad (4)$$

Where WUE is the water-use efficiency (kg ha^{-1} mm^{-1}), Y (kg ha^{-1}) grain yield, and ET (mm), evapotranspiration.

2.4. Statistical analysis

SAS 6.2 was used for variance analysis. F-test was used for the significance of treatment. Multiple comparisons of means were performed with level of $P \leq .05$ using Duncan's multiple range test (Duncan, 1955).

3. Results

3.1. Soil bulk density and pH

There was no significant difference in soil bulk density among each treatment in the first three years of fertilization (Fig. 1). HS treatment significantly decreased soil bulk density compared with CK after the fourth year of straw application, by 4.8% in 2010 and 5.6% in 2011. Soil bulk density of each treatment was decreased from 2007 to 2011. The decrease range of soil bulk density from 2007 to 2011 increased