Soil & Tillage Research 160 (2016) 65–72

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Effects of straw incorporation on the soil nutrient contents, enzyme activities, and crop yield in a semiarid region of China

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ARTICLE INFO

Article history:
Received 25 August 2015
Received in revised form 1 February 2016
Accepted 12 February 2016
Available online 1 March 2016

Keywords:
Soil nutrients
Soil organic carbon
Soil enzyme activities
Straw incorporation
Crop yield

ABSTRACT

The current cropping system of conventional tillage and stubble removal in the northwestern Loess Plateau of China is known to decrease the water use efficiency and crop yield because of soil infertile and degradation. To determine the effects of straw incorporation on the soil fertility and crop yield, we conducted experiments in semiarid areas of southern Ningxia for 4 years (2007–2010). Four treatments were tested: (i) no straw incorporation (CK); (ii) incorporation of maize straw at a low rate of 4500 kg ha^{-1} (L); (iii) incorporation of maize straw at a medium rate of 9000 kg ha^{-1} (M); and (iv) incorporation of maize straw at a high rate of 13500 kg ha^{-1} (H). After straw incorporation for four years, the results showed that variable straw amounts had different effects on the soil fertility indices, where H treatment had the greatest effect. Compared with CK, the average soil available N, total N, available P, total P, and SOC levels under straw incorporation treatments were 27.5%, 10.8%, 16.6%, 5.2%, and 9.8% higher in 0–40 cm soil layers, especially in 0–20 cm soil layer. The straw incorporation treatments average increased the soil urease, phosphatase, and invertase activities levels by 19.6%, 39.4%, and 44.3% in 0–60 cm soil layers, according to the following order: H > M > L > CK. And higher yields coupled with higher nutrient contents were achieved with H, M and L compared with CK, where these treatments increased the crop yields by 22.5%, 22.8%, and 10.6%, and water use efficiency by 34.6%, 30.7%, and 15.7%, respectively. Our results suggest that straw incorporation (especially in rate of 13500 kg ha^{-1}) is an effective practice for improving the soil fertility and increased crop yield in semiarid region of China.

1. Introduction

In recent years, there has been much emphasis on the issue of sustainability in dryland agricultural systems (Singh and Singh, 1995; Deng et al., 2006; Jin et al., 2009), where water and low soil fertility are two major constraints that affect increased agricultural production and its stabilization. In northwest China, the rain-fed soils in semiarid areas are usually infertile and water deficient (Huang et al., 2005; Deng et al., 2006). Thus, it is important to improve the soil fertility, which could significantly promote increases in crop productivity in this area. Since the 1980s, the burning of crop residues has been performed for disposal after the harvest in northwest China. However, burning crop residues decreases the amount of C and nutrients returned to the soil, especially N and P (Prasad et al., 1999; Chan et al., 2002; Wuest et al., 2005) Furthermore, the use of excessive amounts of chemical fertilizer can increase crop productivity but it also leads to degradation of the agricultural environment and pollution (Mandal et al., 2004). Many studies have shown that crop straw is rich in organic materials and soil nutrients, so it is increasingly considered to be an important natural organic fertilizer, which could replace chemical fertilizers (Dick et al., 1988; Duiker and Lal, 1999; Saroa and Lal, 2003; Tan et al., 2007; Bakht et al., 2009).

Previous studies have demonstrated that the concentrations of soil nutrients (e.g., organic C, N, and P) are good indicators of soil quality and productivity because of their favorable effects on the physical, chemical, and biological properties of soil (Karami et al., 2012). Soil microbial properties, such as soil enzymes, are important in all biochemical processes that occur in the soil

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http://dx.doi.org/10.1016/j.still.2016.02.006
0167-1987/

environment and they are closely related to nutrient cycling, energy transfer, and environmental quality (Yao et al., 2006; Jiao et al., 2011); therefore, they have been used to predict the soil biological status and the effects of farm management practices on soil quality (Eivazi et al., 2003).

The incorporation of straw directly or indirectly into cultivated soils can promote the production of a favorable soil environment (Mulumba and Lal, 2008), as well as alleviating the soil degradation caused by intensive and continuous conventional tillage (Lou et al., 2011). Several studies have demonstrated the beneficial effects of crop residue incorporation for improving the soil fertility (Tan et al., 2007; Jin et al., 2009). Li et al. (2010) reported that straw incorporation can replenish the soil organic matter content by enhancing carbon inputs. Dolan et al. (2006) and Tong et al. (2014) showed that the addition of plant residues may facilitate the transformation of fertilizers or soil nutrients into a slowly available nutrient source, thereby improving the nutrient utilization efficiency.

Studies have also shown that straw incorporation has significant effects in improving the activity levels of soil enzymes (Garg and Bahl, 2008). In particular, Sun et al. (2003) showed that the incorporation of maize straw increased the levels of phosphatase, urease, and invertase over a 12-year period, where the enzyme activity was related to the soil organic matter content of the soil. In addition, Jin et al. (2009) found that the crop productivity was positively related to the activities of enzymes under different tillage management systems.

Several studies have reported the effects of straw incorporation on the physical properties of soil (e.g. the soil structure, soil water content, etc.) (Mandal et al., 2004; Zhang et al., 2014), but there have been few analyses of the biological status of soil in rain-fed agricultural systems, particularly in the semi-arid Loess plateau region of China. In this area, dryland crops account for much more of the agricultural area than irrigated crops, which makes them especially economically important. In the present study, we aimed to determine the effects of different straw incorporation rates on the organic carbon levels, nutrient contents, and enzymatic activities of soil, as well as evaluating the soil fertility characteristics under straw incorporation in this important agricultural region.

2. Materials and methods

2.1. Site description

The field experiments were conducted over four growing seasons from 2007 to 2010 at the Dryland Agricultural Research Station, Pengyang County, Ningxia, China (106°45′N, 35°79′E and 1800 m a.s.l.). The station is located in a hilly and gully area of the Loess Plateau, which is characterized by a semiarid, warm temperate, and continental monsoon climate. The average annual precipitation was 435 mm, mainly from June to September. The annual temperature average was 8.1 °C and the annual mean evaporation was 1050 mm, with a frost-free period of 155 days.

During the experimental period, rainfall was measured using an automatic weather station (WS-STD1, Delta-T, UK) at the experimental site.

The soil at the experimental site was a loessal soil with a pH of 8.5. In the 0–40 cm soil layer, the organic matter, total N, P, and K were 8.32 g kg^{-1}, 0.61 g kg^{-1}, 0.58 g kg^{-1}, and 5.4 g kg^{-1}, respectively, while the available N, P, and K were 46.25 mg kg^{-1}, 10.41 mg kg^{-1}, and 104.82 mg kg^{-1}. In 2007, the site was planted with maize prior to the experiment.

The experimental field was flat and, according to the FAO/UNESCO Soil Classification (FAO/UNESCO 1993), the soil was a Calcic Cambisol (sand 14%, silt 26%, and clay 60%) with low fertility.

2.2. Experimental design and field management

This experiment used a randomized block design with three replicates. Each plot was 3 m wide and 6 m long. The experiment included four straw incorporation treatment rates: (i) no straw incorporation (CK); (ii) incorporation of maize straw at a low rate of 4500 kg ha^{-1} (L); (iii) incorporation of maize straw at a medium rate of 9000 kg ha^{-1} (M); and (iv) incorporation of maize straw at a high rate of 13500 kg ha^{-1} (H).

Before mixing with the soil, the maize straw was chopped into 5-cm pieces. The maize straw was then mixed manually with the top 25 cm of the soil in the field. The straw was applied to the soil for 6 months before the crop was planted to facilitate the decomposition of the straw. Straw was incorporated into the soil layer on October 15, 2006 and after the harvests in 2007, 2008, and 2009. The crop rotation comprised maize–millet–maize–millet. Maize (cv. Shendan 16, *Zea mays* L.) was sown at a rate of 52500 plants ha^{-1} in mid-April using a hole-sowing (3 cm in diameter) machine and harvested manually in mid-October during 2007 and 2009. Millet (cv. Datong 10, *Setaria italica* L.) was sown at a rate of 300000 plants ha^{-1} by manual drilling in early April and harvested in early October during 2008 and 2010, where the millet samples were dehulled twice using a rice huller (JLGJ4.5, Zhejiang Taizhou Food Instrument Factory, China) to calculate the yields.

Ten days before sowing, a basic fertilizer containing 102 kg N ha^{-1} and 90 kg P ha^{-1} was spread evenly over each plot and plowed into the 10–20 cm soil layer by spade manually. No artificial irrigation was provided during the years of the experiment. Manual weeding was performed throughout the experiment. And electrical sprayer (3WBD-16, Taizhou Minghui electric sprayer company, China) was used to control the pests during the crops growth period.

2.3. Sampling and measurement

Rainfall data were recorded using a standard weather station at the experimental site. After the crop harvest in each year from 2007 to 2010, soil samples were collected manually using a 54-mm diameter steel core-sampling tube (T-54, Yangling Machine Equipment Factory, China) for each of the four incorporation treatments. Soil samples (approximately 500 g) were collected from each plot at depths of 0–20 cm and 20–40 cm to determine the soil nutrient contents, and at depths of 0–20 cm, 20–40 cm, and 40–60 cm to determine the soil enzyme activities. The soil samples were collected from four points in each plot replicate and mixed to produce a composite sample. Each soil sample was passed through an 8-mm sieve by gently breaking the soil clods, whereas pebbles, weeds straw, and stable clods >8 mm were discarded. The soil samples (approximately 200 g) were air-dried for 24 h in the laboratory before analyzing the soil nutrients. Other soil samples (approximately 300 g) were stored immediately at 4 °C before analyzing the soil enzyme activities.

All of the analyses were based on published Physical and Chemical Analysis Methods of Soils (ISSCAS, 1978). Soil organic carbon (SOC) was determined using the Walkley-Black method. Briefly, 10 mL of 1 N potassium dichromate + 20 mL of concentrated H_2SO_4 solution were added to 0.1 g of sieved and dried soil, which were then mixed by gentle rotation for 1 min and treated at 150 °C for 10 min, before cooling to room temperature. The samples were then diluted to 200 mL with deionized water, and 10 mL of phosphoric acid, 0.2 g ammonium fluoride, and 10 drops of diphenylamine indicator were added. Finally, the excess dichromate was titrated with Morh salt solution (0.5 N $FeNH_4SO_4$ and 0.1 N H_2SO_4). Soil total nitrogen (TN) was determined using an automatic Kjeldahl distillation-titration unit (Foss, Sweden). The soil available nitrogen (AN) was converted to NH^{4+} under alkaline