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Crop yield and soil properties of dryland winter wheat-spring maize rotation in response to 10-year fertilization and conservation tillage practices on the Loess Plateau

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A B S T R A C T

Drought and nutrient deficiency are the principal factors limiting crop production in arid and semi-arid areas. Conservation tillage can maintain and increase grain yields by enhancing soil fertility and conserving more soil water in the field. However, farmers without access to mineral fertilizers cannot compensate for the soil nutrient deficiencies for crop production, and the crops will suffer yield reductions. Site-specific fertilizer application with conservation tillage practice management is the key to achieving a high and sustainable crop yield. A long-term (2007–2016) two-factor, spilt-plot experiment was established to assess the effects of fertilization {balanced fertilization (BF), low fertilization (LF), conventional fertilization (CF)} and conservation tillage practices {no tillage (NT), subsoiling (ST), conventional tillage (CT)} on grain yield, soil water and soil nutrients. The aim of this experiment was to select an optimal fertilization and tillage management system for crop production in the Loess Plateau, a typical semi-arid and rainfed area of China. Ten-year data showed that subsoiling with balanced fertilization (BST) increased the grain (6465 kg ha^{-1}) and straw yield (9792 kg ha^{-1}), but no tillage with balanced fertilization (BNT) was observed to provide the highest economic profit for farmers (6416 yuan ha^{-1}). No tillage with low fertilization (LNT) was the optimal management for soil water conservation in fields that could preserve more soil water in fallow land (mean value: 425 mm) and provide more soil water during the wheat (mean value: 387 mm) and maize (mean value: 420 mm) growth season. The LNT consumed less soil water in the crop growth season (mean value: 105.4 mm), but the BST (18.5 kg ha^{-1} mm^{-1}) showed a higher water use efficiency (WUE). The BF and NT showed better soil nutrient conditions (soil organic matter(SOM), available N, P and K) over the ten years and provided better soil water and balanced soil nutrient conditions for crop growth. The BNT and BST were recommended as the optimal and economic fertilization with tillage management systems for maintaining high grain yields by using soil water efficiently and enhancing soil fertility in a winter wheat-spring maize rotation on the Loess Plateau.

1. Introduction

Drought and nutrient deficiency are the principal factors limiting crop production in arid and semi-arid areas (Austin, 2011; Rockstrom and deRouw, 1997; Sadras, 2005). In China, dryland farming holds an important status in agriculture, and approximately 40% of the arable dryland is situated on the semi-arid Loess Plateau (Li, 2004). As a major grain-based area in China, it is urgent that drought and depleted soil conditions in the Loess Plateau be resolved (Wang et al., 2009).

Previous studies on the Loess Plateau (Dai et al., 1996; Li et al., 1990) found that the critical factor that limited the yield was soil fertility rather than drought. Soil fertility is the basis to sustain the development of agriculture; thus, enhancing soil fertility is the key approach in the production of sustainable agriculture (Wen et al., 2015). Fertilization is one of the important measures that can enhance soil fertility. The crop yield increased with increasing fertilization within a certain range (Zhang et al., 2015). However, driven by the desire for higher crop yields, the rate of fertilization has reached a relatively high level by increasing fertilizer applications in recent years (Wang et al., 2009). Over-fertilization has recently become a common practice for farmers, but it does not always contribute to high grain yields (Xu et al., 2015). Unfortunately, inappropriate or excessive fertilizer application does not guarantee constantly increasing yields, which may result in low nutrient use efficiency, and thus cause a series of economic and environmental problems (Guo et al., 2010; Ju et al., 2006; Peng et al., 2006; Tilman et al., 2011). Moreover, excessive

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fertilization and high crop yield production annually augmented water consumption in fields, and soil water restricted crop production in consecutive years with rare and erratic rainfall (Zhang et al., 2015; Wang et al., 2009). Therefore, how to improve the soil water status and optimize the coupling of fertilization and water are key to obtaining high and sustainable crop yields in arid areas.

Conservation tillage practices, including crop residue cover, and reduced and no tillage, have been proposed as new practices to maintain and increase grain yields by enhancing soil fertility, reducing seasonal evapotranspiration and conserving more soil water (Aziz et al., 2013; Li et al., 2007). There is no doubt that the dominant advantage of conservation tillage is to conserve more soil water (Fabrizzi et al., 2005; Lampurlanes et al., 2016). In addition, crop residues are the direct sources of organic C and soil NPK. Along with enhanced soil physical properties, several researchers have noted that crop residues had significant effects on the improvement of SOC, soil N and other nutrients (Bhattacharyya et al., 2015; Jalota et al., 2008). Recycling crop residues in conservation tillage is an effective practice that can reduce the application of mineral fertilizers, maintain soil fertility, improve soil properties and support sustainable crop production in cropping systems (Wang et al., 2015). However, these positive effects on enhanced soil fertility are limited, and this practice cannot replace fertilizer, which satisfies crop growth and maintains a sustainable and high crop yield. Without the application of mineral fertilizer, crop residue recycling cannot compensate for nutrient deficiencies in fields, and farmers will suffer yield reductions as a direct result (Giller et al., 2009).

The supplementary use of organic and inorganic fertilizers holds the key to sustainable agricultural productivity and has been proven as a sound fertility management strategy in many countries worldwide (Lombin et al., 1991). Apart from enhancing crop yields, the practice also has a great beneficial residual effect on soil nutrients. A proper and site-specific fertilizer application with tillage practices can increase water availability for crops by increasing soil water storage capacity, reducing soil evaporation and allowing a high and sustainable crop yield (Agbede, 2010; Lampurlanés et al., 2001). Proper fertilization with conservation tillage management may lead to better crop performance and soil conditions in fields. With this in mind, a long-term experiment was established in a field in Heyang County, Shaanxi Province, a region typical of the semi-arid Loess Plateau of China, to assess the effect of fertilization and conservation tillage practices on agricultural ecosystem productivity. In this paper, a long-term (2007–2016) two-factor, spilt-plot experiment was established to assess the effects of fertilization {BF (balanced fertilization), LF (low fertilization), CF (conventional fertilization)} and conservation tillage practices {NT (no tillage), ST (subsoiling), CT (conventional tillage)} on grain yield, soil water and soil nutrients. This was aimed at selecting an optimal fertilization and tillage management system for crop production in semi-arid agriculture.

2. Materials and methods

2.1. Study site description

The field experiment was conducted over ten growth seasons, from September 2007 to June 2016, at the Dryland Agricultural Research Station of Northwest A&F University, which is located in Ganjing (35°19′N, 106°4′E), Heyang County, Shaanxi Province, China. The research station was located on the Loess Plateau, which is characterized by a temperate semi-arid continental monsoon climate at an altitude of 877 m. The annual mean temperature and evaporation were 11.5 °C (Fig. 1) and 1833 mm, respectively. Over the last 30 years, the annual mean precipitation was 526 mm (Fig. 1). The annual precipitation displayed an uneven distribution, 60% of which mainly occurred during the summer season (July, August, and September) that deviated from the winter wheat growth season. The meteorological data was derived from the local weather station at Heyang County which is 12 km away from the experimental site (Ganjing town).

Before the experiment of 2007, continuous spring maize was planted annually, and conventional tillage (mouldboard plowing) with crop residue removal was applied every year after crop harvest. The field experiment was conducted on level terrain with dark loessal soil, which is a typical soil type in the Loess Plateau, and is classified as middle loam soil based on the FAO/UNESCO Soil Classification (1993). The soil properties and nutrient conditions at a soil depth of 0–60 cm before this experiment started in 2007 are shown in Table 1.

2.2. Experimental design and treatments

The field experiment was laid out with three fertilizations (balanced fertilization (BF), low fertilization (LF) and conventional fertilization (CF)) as main treatments and was spilt into three tillage practices (continuous no tillage (NT), continuous subsoiling (ST) and continuous conventional tillage (CT)) as sub treatments. Each sub-plot was 5 m wide and 22.5 m long (112.5 m^2) with a 60-cm interval between plots. Winter wheat and spring maize were sown at a density of 3.3 million plants ha^{-1} and 60 thousand plants ha^{-1}, respectively. The row spaces for winter wheat and spring maize were 20 cm and 60 cm, respectively. The operation of tillage practices and crop planting details are listed in Table 2.

All fertilizers were once manually and evenly spread on the ground both before the sowing time of winter wheat and spring maize each year. The quantities of fertilizers were the same of winter wheat and spring maize. For the balanced fertilization (BF), 150 kg N ha^{-1}, 120 kg P_2O_5 ha^{-1}, and 90 kg K_2O ha^{-1} were applied before sowing each year to the soil as urea, diammonium phosphate, and potassium chloride, respectively. For the low fertilization (LF), 75 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1}, and 45 kg K_2O ha^{-1} were applied before sowing each year to the soil as urea, diammonium phosphate, and potassium chloride, respectively. For the conventional fertilization (CF), 255 kg N ha^{-1} and 180 kg P_2O_5 ha^{-1} were applied before sowing each year to the soil as urea and diammonium phosphate, respectively. The soil in the Loess Plateau is rich in potassium (K), and the soil total K is relatively high; thus, farmers generally apply fertilizers to the field without potassium. Conventional fertilization (CF) was determined according to the mean fertilization level of the local farmers. Balanced fertilization (BF) was applied at the recommended rate determined by the local soil nutrient conditions and adequate nutrient ratios of crop production. The rate of the low fertilization (LF) was half that of the balanced fertilization.

For the NT treatment, the crop straw was chopped and spread evenly on the surface of the experiment plots after the harvest of the previous crop using a combine harvester. No other soil disturbance was applied before crop sowing. For the ST treatment, the crop straw was left on the soil surface as mulch, and the soil was then subsoiled to a depth of 30–35 cm with an interval of 60 cm by a subsoiler with adjustable wings. The surface soil had little disturbance with the ST treatment. For the CT treatment, the crop straw was incorporated into the soil layer and plowed to a depth of 22–25 cm. All tillage practices were applied after the crop harvests. Winter wheat and spring maize were harvested by a Guwang TB60 (ZOOMLION Co. Ltd., Hebei, China) and CC40 (ZOOMLION Co. Ltd., Hebei, China), respectively. For the NT and ST practices, all crop straw was chopped and left on the soil surface as mulch in each plot, and the amount of crop residues retained on the surface was approximately 40–70% during fallow period. At the sowing time of spring maize, the extent of the surface cover was approximately remained 15–20% in NT and ST practices. The crop straw in the CT treatment was all chopped and incorporated into the soil layer with a bare soil surface in each plot. There was a one-time herbicide sprayed in late July during the fallow period, and no other soil disturbance was applied before sowing. To reach a good soil condition for crop emergence and fertilizer mixing, rotary tillage was applied at the crop sowing, one time each year.