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Effects of different sub-soiling frequencies incorporated into no-tillage systems on soil properties and crop yield in dryland wheat-maize rotation system

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ABSTRACT

No-tillage has become a universal management system to conserve soil water and sustain soil productivity in dryland agriculture. However, no-tillage in a long-term may produce some undesirable soil characteristics. An occasional tillage operation has been used as a mean to manage some of the defects that have emerged in NT farming systems. This study was to explore the effect of sub-soiling at different frequencies in a no-tillage farming system of an annual cropping system of winter wheat-spring maize rotation on Loess Plateau. The study consisted of three tillage practices: NT (no-tillage were applied every year), NT/ST (no-tillage were applied in first year and rotated with sub-soiling in second year), NT/NT/ST (no-tillage were applied in first two year and rotated with sub-soiling in third year). The study began in 2007 on a former spring maize field with conventional tillage and lasted for three-year rotation cycles by 2016. In ten years, for the soil physical properties, NT/ST rotation significantly decreased soil bulk density, and increased soil porosity and amount of macroaggregates (> 0.25 mm) when compared to NT ($P < 0.05$). For water storage, NT with ST rotations (NT/ST & NT/NT/ST) increased the soil water storage in the fallow periods. Moreover, NT/ST rotation produced higher average grain yields, WUE and economic profit in the winter wheat-spring maize cropping system when compared to NT over the ten years. However, the soil organic matter (SOM) and total N under NT with ST rotations (NT/ST & NT/NT/ST) were lower than it for NT. For this long-term experiment, NT provided a better soil nutrient condition, NT/NT/ST and NT/ST rotation showed a better effect on soil water storage in fallow. For the comprehensive productivity, NT/ST rotation showed a balanced soil properties and crop production effect among three tillage treatments. In the winter wheat-spring maize cropping system, NT/ST rotation enhanced soil physical and chemical properties and increased yield and water holding capacity of soil. We predict that the NT/ST rotation will be of great significance in promoting the development of rain-fed conservation farming in the Loess Plateau of China.

1. Introduction

The semi-arid areas of the Loess Plateau, which belong to a temperate semi-arid continental monsoon climate zone, are of crucial importance for arid agriculture in China (Bai et al., 2014). These semi-arid agricultural areas in North China are typically rain-fed, and the annual and seasonal distribution of precipitation is varied. Drought and water scarcity are the main limiting factors of local grain production (Yang and Shao, 2000). Straw mulch, reduced tillage and soil disturbances, and/or conservation tillage could improve conservation of water in the soil and water use efficiency (WUE) (Moreno et al., 1997; Wang et al., 2015). Many studies point out that conservation tillage enhances soil properties, and increase crop yields (Barber et al., 1996; Carter et al., 2009; Hou et al., 2012; Jia et al., 2002; Liu et al., 2004; Twomlow et al., 1994). The covering of crop residues, reduced tillage and no tillage are the most effective measures to control soil and water loss (Gao et al., 2003). These practices have become a focus in the study of dryland agriculture, and no-tillage is considered one of the essential soil management measures of dryland farming.

No-tillage plays a major role in conservation agriculture. Compared to conventional tillage, Balota et al. (2014) and Shahidi et al. (2014) found that no-tillage could enhance the content of soil organic carbon

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and increase the activity of soil microorganisms. They also found that no-tillage was conducive to the formation of soil aggregates and improved the properties of the soil. No-tillage has revolutionized agricultural systems by allowing growers to manage greater areas of land with reduced energy and machinery inputs (Triplett and Dick, 2008). However, no-tillage in a long-term may produce some undesirable effects, such as a build-up of herbicide resistance in perennial weeds, an increased incidence of soil- and stubble-borne diseases and/or a stratification of immobile nutrients and soil carbon at or near the soil surface (Thomas et al., 2007). No-tillage can also lead to higher soil bulk density and reduced topsoil, which creates unfavorable conditions for water movement and soil conservation (Hou et al., 2012; Kong et al., 2010). Long term of no-tillage may cause soil bulk density to increase, which may lead to decreased root absorption of soil nutrients and water, hence lower yields (Birkas et al., 2004; Martinez et al., 2008). Strictly no soil disturbance may result in undesirable damage to the soil. An occasional tillage operation has been used as a mean to manage some of the defects that have emerged in NT farming systems (Dang et al., 2015; Kettler et al., 2000; Ma et al., 2015). However, a one-time tillage operation may undo much of the positive effect of NT farming systems on soil conditions. And specifically, the effect of the occasional ST in a continuous NT farming system is not yet clearly understood.

In this study, we systematically analyzed the data for a long-term experiment of ten consecutive years, from 2007 to 2016, about the frequency of subsoiling (ST) in a no-tillage (NT) farming system of winter wheat-spring maize rotation field conducted in the typical semi-arid dryland farming area of the Loess Plateau. This paper was to explore the effects of soil properties and yields of wheat-maize rotation cropping system for different ST frequencies under a long-term no-tillage system. Our results from this ten-year (from 2007 to 2016) field study, can help optimize the selection of ST frequency in no-tillage of wheat-maize rotation fields on the Loess Plateau, as well as provide a theoretical basis for improving soil productivity, yields and water conservation, and addressing practical issues related to the popularization of no-till agriculture, especially with the additional use of ST at varying frequencies in semi-arid no-tillage farming systems.

2. Materials and methods

2.1. Study site description

The field experiment was conducted over ten growing seasons from September 2007 to June 2016 at the Dryland Agricultural Research Station of Northwest A & F University, which was located in Ganjing town (35°19′N, 106°4′E, and 877 m asl), Heyang County, Shaanxi Province, China. The research station was located in the Loess Plateau, which is characterized by a temperate semi-arid continental monsoon climate. The annual mean temperature and evaporation were 11.5 °C and 1833 mm, respectively. Over the last 30 years, the annual mean precipitation was 526 mm of which 60% occurred in July, August, and September. The total yearly frost-free period was 210 days. Before the experiment, continuous spring maize was planted, and conventional tillage was applied after the harvest of crop every year. The field experiment was conducted on level terrain with dark loessial soil which is a typical soil type in the Loess Plateau, and it is classified as middle loam soil based on the FAO/UNESCO Soil Classification (1993). The soil properties and nutrient conditions at the soil depth of 0–60 cm before this experiment started in 2007 are shown in Table 1. The weather data were recorded using a standard weather station on the experimental site.

2.2. Experimental design and treatments

In this study, three tillage treatments in fallow period of wheat-maize rotation field were applied for ten years: NT (no-tillage were applied every year), NT/ST rotation (no-tillage were applied in first year and rotated with sub-soiling in second year), NT/NT/ST rotation (no-tillage were applied in first two year and rotated with sub-soiling in third year). Three complete cycles of three-year rotations were performed during the ten years (2007–2016). NT and ST tillage treatments were applied after the crop harvests. For NT treatment, the crop straws were chopped and spread evenly on the surface of the experiment plots after the harvest of the previous crop by using a combine harvester. For ST treatment, the crop straws were left on the soil surface as mulch and the soil was then subsoiled to a depth of 30–35 cm with interval 60 cm distance by a subsoiler with adjustable wings. The surface soil had little disturbance with the ST treatment. In this treatment, the soil had no disturbance before sowing. The seeding rate of winter wheat and spring maize were 150 kg ha^{-1} and 75 kg ha^{-1}, respectively. The operation of tillage practices and crop planting details are listed in Tables 2 and 3. In this experiment, 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.

Table 1
Basic physical and chemical properties of the soil in 2007.

Soil depth (cm)	Bulk density (g cm^{-3})	Organic matter (g kg^{-1})	Total N (g kg^{-1})	Total P (g kg^{-1})	Total K (g kg^{-1})	Alkali-hydrolyzale N (mg kg^{-1})
0–20	1.34	10.48	0.65	0.60	5.92	36.57
20–40	1.48	7.96	0.45	0.18	5.53	18.90
40–60	1.44	4.90	0.43	0.06	5.79	12.14

2.3. Measurements and data analysis

All soil samples were collected for three repetitions after crop harvest. The samples for nutrients and bulk density were collected from three depths (0–20 cm, 20–40 cm, 40–60 cm) under three tillage systems. The soil bulk density was measured from undisturbed soil cores. Soil cores were weighed wet, dried in a convection oven at 105 °C for 8 h, and weighed again to determine the soil water content and bulk density (Ferraro and Ghersa, 2007). Gravimetric water content was multiplied by soil bulk density to obtain the volumetric water content. Soil water storage was calculated for a 2.0 m profile by multiplying the mean soil volumetric water content by soil profile depth. The soil moisture storage was measured by using a 5 cm soil auger at 20 cm increments down to 200 cm in all experimental plots. The soil water content was determined using the oven-drying method. The yield of crop was determined by manual harvesting, threshing, and air-drying grain from three 3 m^2 and 9 m^2 areas taken at random in each plot for winter wheat and spring maize, respectively.

In each plot, soil samples were taken by using a 5 cm soil auger in five random points to determine soil nutrients. Each sample was sieved through 1 mm and 0.25 mm screens into plastic bags for soil nutrient analysis. Organic matter was extracted by the K_2CrO_7-H_2SO_4 heat treatment, and residue was determined using the $FeSO_4$ titration of potassium dichromate method. Nitrogen was determined by using the Kjeldahl method (Tan et al., 2015).

The soil samples for aggregates were collected from four depths (0–10, 10–20, 20–30 and 30–40 cm). The soil water-stable aggregate distribution was determined by the wet-sieving method; the sample was placed on a stack of sieves (5, 2, 1, and 0.25 mm), then manually immersed in water and moved up and down by 3.5 cm at a frequency of 30 cycles per minute for a total of 50 cycles. Aggregate size proportions of 5–2, 2–0.25, and < 0.25 mm were calculated by drying and weighing the soil remaining on the sieves (Oades and Waters, 1991).

The requisite indices were calculated according to the following formulae.

W_i (%) = (wet soil weight- dried soil weight)/dried soil weight × 100%