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Effects of rotational tillage practices on soil properties, winter wheat yields and water-use efficiency in semi-arid areas of north-west China

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ABSTRACT

Soil degradation caused by continuous conventional tillage and long-term minimum and no-tillage in rain-fed areas of north-west China is known to reduce water-use efficiency and crop yield, because of the reduced soil porosity and decreased availability of soil water and nutrients. A 3-year field study was conducted to determine the effects of interval with no-tillage and subsoiling to overcome some of the tillage after crop harvesting on soil properties, crop yields and water-use efficiency in semi-arid areas of southern Ningxia. Three tillage treatments were tested: conventional tillage (CT) for 3 years as the control; no-tillage in year 1, subsoiling in year 2, and no-tillage in year 3 (NT/ST/NT); subsoiling in year 1, no-tillage in year 2, and subsoiling in year 3 (ST/NT/ST). The mean soil bulk density of tilth soil (0–40 cm) was significantly decreased by 3.5% and 6.2% compared with CT under NT/ST/NT and ST/NT/ST, respectively, and both treatments greatly improved total soil porosity. Rotational tillage could increase water-stable aggregates, soil organic matter and the available N and P content. Rotational tillage significantly in the 0–40 cm soil layers, with a higher effect under ST/NT/ST. Rotational tillage significantly improved soil water status, increased the amount of soil water stored during the summer fallow and wheat growing season compared with conventional tillage. Higher yield improvements coupled with greater water-use efficiency were achieved with NT/ST/NT and ST/NT/ST compared with CT, and these treatments increased wheat yields by 9.6% and 10.7%, along with water-use efficiency improvements of 7.2% and 7.7%, respectively. The results showed that the interval of no-tillage and subsoiling (rotational tillage) could improve soil physical and chemical properties, and thus significantly increase crop yields and water-use efficiency. This method could have important applications in the semi-arid areas of north-west China.

1. Introduction

Rain-fed cropland accounts for ~80% of the total cultivated land in the semi-arid areas of north-west China (Shan and Cheng, 1993). Average annual rainfall is 450 mm, but the rainfall distribution is uneven, with 70% of the rainfall occurring during July–September, and there is a high rate of evaporation (Kang et al., 2001). Water deficiency is a major factor limiting crop growth in semi-arid areas (Mupangwa et al., 2008). Traditional farmers use conventional tillage after wheat harvesting to improve soil moisture (Huang et al., 2003). Nevertheless, many studies have demonstrated that the excessive tillage applied with the conventional system increases soil bulk density (Fabrizzi et al., 2005), decreases macro-porosity and macroaggregates (Chen et al., 2007), reduces water and nutrient availability (Su et al., 2007; He et al., 2009), and leads to unstable and declining crop yields (Chan and Heenan, 2005).

No-tillage (NT) and subsoiling are known to be effective tillage practices (Li et al., 2007; He et al., 2007, 2009). NT management decreases soil disturbance, reduces soil bulk density, and improves aggregate stability (Oyedele et al., 1999; Zhang et al., 2007). Subsoiling can improve soil structure by eliminating soil compaction, and increase both yield and water use efficiency (*WUE*) (Pikul and Aase, 1999; Pikul and Kristian, 2003). However, other studies found that long-term NT farming caused soil compaction (Cassel, 1995), and annual subsoiling had very little effect on soil water conservation over three cropping seasons (Evans et al., 1996). Thus, long-term NT and annual subsoiling can lead to some soil quality problems, which is not favorable to crop growth and yield improvement.

Relative studies showed that NT coupled with subsoiling practice can increase crop yields and *WUE* in semi-arid areas of northern

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China (He et al., 2006), and adopting soil rotational tillage at an appropriate time is an effective method for overcoming some of the disadvantages caused by continuous single tillage (Carter et al., 2002; López-Fando et al., 2007). He et al. (2007) showed that the subsoiling effect lasted about 4 years and that subsoiling tillage was not required every year, and a 4-year NT planting operation, plus 1 year of subsoiling minimized soil compaction caused by random wheel traffic and it resolved some problems of frequently disturbed soil and lower *WUE* caused by annual subsoiling. Qin et al. (2008) also found that subsoiling with NT 2 years significantly increased crop yields, and improved the water use because of improved soil physical and chemical properties. Current information is limited on the responses of soil physical and chemical characteristics, crop yields and *WUE* to an interval with NT and subsoiling in the semi-arid areas of north-west China.

We hypothesized that new tillage interval program with NT and subsoiling could improve soil physical and chemical properties, and significantly increase crop yields and *WUE* by improving soil structure, thereby enhancing availability of soil water and nutrients. The present study investigated rotational tillage (an interval with no-tillage and subsoiling), and the main objective of this research was to evaluate the effects of tillage practices after wheat harvesting on soil properties, crop yields and *WUE*, and to provide a scientific basis for establishing a methodical cropping system.

2. Materials and methods

2.1. Site description

The experiment was conducted between 2007 and 2010 in the Dryland Agricultural Research Station, Pengyang County, Ningxia, China (106° 45′ N, 35° 79′ E, 1800 m above sea level). The experimental area was in the hilly and gully region of the Loess Plateau, which is characterized by a semi-arid, warm temperate, continental monsoon climate, with an average annual rainfall of 435 mm falling mainly from June to September. The annual mean evaporation is 1050 mm and annual temperature average 8.1 °C, with a frost-free period of 155 days. Mean annual rainfall and distribution of monthly rainfall during the study period from 2007 to 2010 are shown in Fig. 1. Total rainfall volumes for 2007–2008, 2008–2009, and 2009–2010 were 331.4, 370.0, and 427.8 mm, fallow period rainfall volumes were 174.1, 255.6, and 198.2 mm, and wheat growing season volumes were 157.1, 114.4, and 229.6 mm.

The experimental field was flat according to the FAO/UNESCO Soil Classification (FAO/UNESCO, 1993), and the soil was a Calcic Cambisol (sand 14%, silt 26%, clay 60%) with low fertility. The key physical and chemical properties of the soil layers (0–40 cm depth) are listed in Table 1.

2.2. Experimental design and field management

The experiment was a randomized block design with three replicates. Each plot was 5 m wide and 9 m long. The experiment included three tillage treatments: (i) NT after wheat harvest in year 1, subsoiling after wheat harvest in year 2, and NT after wheat harvest in year 3 (NT/ST/NT); (ii) subsoiling after wheat harvest in year 1, NT after wheat harvest in year 2, and subsoiling after wheat harvest in year 3 (ST/NT/ST); (iii) conventional tillage for years 1–3 (CT).

No-tillage was applied in the fallow period, where a 5–8 cm wheat stubble height was left after the winter wheat was harvested, and the wheat was directly drilled in all plots in late September. Subsoiling used a subsoiling chisel point with adjustable wings that was designed at China Agricultural University in 1992. The soil was ploughed to a depth of 30–35 cm with 40 cm between the ploughing strips and the soil was not turned over. The CT treatment consisted of deep ploughing to a depth of 20 cm using a tractor-mounted mouldboard plough and harrowing to a depth of 15 cm, followed by tine tillage for seedbed preparation.

Winter wheat (Xifeng-26) was sown at a rate of 350 seeds m^{-2}, on 18 September 2007, 15 September 2008, and 20 September 2009, using an Amozone NT 250 drill with chisel-type openers and depth-controlling press wheels at a row spacing of 20 cm. The drill also banded N and P fertilizers 5–8 cm below the seeds at two-thirds and the full recommended rates, respectively. Urea ($N \geq 46\%$) and Superphosphate ($P_2O_5 \geq 12\%$) were applied at levels of 675 and 750 kg ha^{-1}, respectively, at planting time. An additional 150 kg ha^{-1} of urea was topdressed at the jointing stage. For each crop cycle, manual weeding was undertaken as required during the experiment period. Wheat was harvested on 27 June 2008, 24 June 2009, and 10 July 2010.

2.3. Sampling and measurement

Rainfall data were recorded using a standard weather station on the experimental site. Soil samples were collected from two depths (0–20 and 20–40 cm) within the three tillage treatments after wheat harvest in 2007 and 2010. In each plot, soil sample was taken to determine soil organic matter and available N and P content. For water-aggregate stability, a similar soil sample was collected at 0–20 and 20–40 cm depths. Each soil sample was first passed through an 8 mm sieve by gently breaking the soil clods, while pebbles and stable clods larger than 8 mm were discarded. Soil samples were air-dried for 24 h in the laboratory before analysis.

Between 2007 and 2010, soil water was determined in each plot by taking three random soil core samples using a 54-mm-diameter steel core-sampling tube, which was manually driven to 2.0 m depth during each follow period (from July to September) and wheat growing season between October and June of the next year. Soil cores were weighed wet, dried in a fan-assisted oven set at 105 °C for 48 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.

Size distribution of water-stable aggregates, soil organic matter, and available N, P were determined by placing a soil sample on a stack of sieves (2, 1, and 0.25 mm). The stack was then immersed in water and moved up and down by 3.5 cm at a frequency of 30 cycles per minute for 15 min. Proportions of >2, 2–0.25, and <0.25 mm were calculated by drying and weighing the soil remaining on the sieves (Oades and Waters, 1991). Soil organic matter was measured by dry combustion using a Leco Carbon Analyzer (Nelson and Sommers, 1982). Available N was extracted with 1 M KCl and analyzed using the cadmium reduction method (Dorich and Nelson, 1984). Available P was extracted with a 0.5 M $NaHCO_3$ solution adjusted to pH 8.5 (Olsen and Sommers, 1982).

Grain yields were determined at 12% water content by manually harvesting three 1-m length rows taken randomly from each plot. Water use efficiency was estimated as the grain yield divided by the growing season evapotranspiration (E) (Hussain and Al-Jaloud, 1995), as follows.

$$WUE = \frac{\text{yield}}{E} \tag{1}$$

The E was calculated using the formula (He et al., 2009):

$$E = P - DW \tag{2}$$