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Long-term evaluation of tillage methods in fallow season for soil water storage, wheat yield and water use efficiency in semiarid southeast of the Loess Plateau

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ABSTRACT

Fallow tillage methods play a major role in improving soil water storage, water use efficiency and hence grain yield in winter wheat (*Triticum aestivum* L.) cropping system in southeast Loess Plateau. However, the efficacy and stability of such methods need to be further validated in long-term field observation. From 2009–2015, a 7-year filed experiment was established in winter wheat fields at Wenxi Agriculture Station, semiarid southeast Loess Plateau. The objectives were to determine the responses of soil water storage, utilization and yield formation to three different tillage

methods: including deep ploughing, subsoiling and no-tillage. Our results indicated that compared to no-tillage, the soil water storage (0–300 cm depth) was averagely increased by 7.8% and 6.0% during fallow season, 13.7% and 9.8% in growing season under deep ploughing and subsoiling respectively. Furthermore, the increasing magnitude in soil water due to deep ploughing and subsoiling was, on average, 10.1% and 5.5% higher in dry season than that in wet one. Improved soil water condition under deep ploughing and subsoiling significantly increased the ear number and grain yield by 20.2% and 15.9%, 30.8% and 25.8% respectively, but did not affect seed number and weight of thousand seed over the experimental seasons. Moreover, grain yields under deep ploughing and subsoiling were averagely increased by 35.2% and 24.8% in dry season, 28.7% and 20.6% in wet season respectively. Accordingly, water use efficiency and precipitation use efficiency were increased by 12.1% and 31.9% under deep ploughing, 11.1% and 25.0% under subsoiling respectively. Critically, we found that with an increase of 10% water storage efficiency during fallow season, ear number, grain yield and WUE could be increased by 0.2 million ha^{-1}, 241.1 kg ha^{-1} and 0.6 kg ha^{-1} mm^{-1} respectively. Our study clearly indicated that deep ploughing in fallow season should be adopted as a promising strategy to retain soil water availability and hence boost wheat productivity in semiarid southeast Loess Plateau.

1. Introduction

Winter wheat (*Triticum aestivum* L.) production plays an extremely important role in southeast of the Loess Plateau, as it is the primary staple food for the people living there. Nevertheless, the yields in this area are often variable and unstable owing to limited and uneven precipitation distribution in both fallow and growing seasons (Kang et al., 2002). In most cases, more than 60% precipitation occurs between July and September, which is main part of fallow season for winter wheat (Huang et al., 2004). Plant is usually subjected to sustained drought during early spring, a critical water consumption stage for vegetative growth. This unmatched supply-demand relationship is worsened by the surface run-off occurred in fallow season. To address these obstacles, many advanced farming practices targeted to improve water availability through retaining precipitation in fallow season have been innovated and applied over last several decades. Among these, conservation tillage (either reduced tillage or zero tillage) is one of most effective options to increase soil water storage, enhance soil organic carbon, improve soil structure, reduce soil erosion, and thereby increase crop yield and agriculture sustainability (Chen et al., 2009). However, long-term and continuous zero tillage can easily lead to soil compaction, especially in top and subsoil layers (Raper et al., 1994). Soil compaction can negatively affect crop yield output through limiting rainwater penetration and hence water & nutrient uptake from

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deep soil (Unger and Kaspar, 1994). In semiarid southeast of the Loess Plateau, the yield reduction due to soil compaction is more remarkable owing to insufficient rainfall storage in fallow season (Jin et al., 2008). Therefore, the efforts aimed to break compacted soil layers should be made to maximize the positive effects of conservation tillage on crop productivity.

Deep ploughing to a depth more than 30 cm is one of the useful practices to alleviate soil compaction through destroying hard pans and decreasing soil bulk density in drought susceptible crop-lands. Hou et al. (2012) recorded that deep cultivation significantly decreased soil bulk density in the 0–40 cm layer, ranging from 3.5% to 6.2% during the study period when compared to conventional tillage. Decreases in bulk density due to deep tillage increase soil porosity, which in turn increases the capacity of soil water storage (Dec et al., 2008). Moreover, deep cultivation of compacted soil could also enhance soil health and ability of plants to resist disease. Laker (2001) pointed that owing to the implement of deep ploughing, the growth stunting disease was eradicated completely and the quality of tobacco (*Nicotiana* spp.) was also increased substantially in semiarid environment. In additional, soil organic carbon is also strongly affected by deep ploughing. A recent study explored the effects of different tillage methods on the changes of long-term soil quality and found that deep ploughing increased agricultural soil organic matter stocks (Alcántara et al., 2016). Along with the improvement of soil water status and quality, seedling establishment, root growth and crop yield are also being increased mainly through improving water infiltration and retention. For instance, Henderson (1991) conducted study with eight crop species and found that the dry matter of all species tested was increased by 30% under the plots of deep tillage, grain yields of field peas (*Pisium satirum* L.) and lupins (*Lupinus micranthus* Guss.) were also increased by 64% and 84% compared to undisturbed plots. Zhao et al. (2013) also found that deep ploughing increased the yield of winter wheat by 31.2% in semiarid southeast Loess Plateau.

Subsoiling is other effective solution for the breaking-up of soil compaction and increasing water storage but without distribution of soil structure. In semiarid north area of China, agronomy scientists have concentrated on subsoiling techniques for the purpose of agricultural sustainability. Guo (2005a) suggested that the subsoiling at a soil depth ranging from 30 to 40 cm could provide an advantage for soil ecology condition and hence improve water use efficiency and crop yield (Qin et al., 2008). Wang et al. (2004) also found that compared to the conventional tillage pattern, subsoiling significantly increased grain yield and water use efficiency of winter wheat by 18.8% and 16.8% respectively. The mechanisms on soil loosening by subsoiling tillage were also explored by comparing three different subsoilers in Shanxi Province (Guo, 2005b). Hu et al. (2013) noted that the application of subsoiling tillage with controlled-release urea could provide a better base for water and nitrogen supply, helping the maize resist drought and boost a higher yield and water use efficiency. Besides soil water, Wang et al. (2014) also found that the adoption of subsoiling improved a number of soil physical attributes and root zone salinity by up to 50% in Loess Plateau.

To our knowledge, in north China, most of the studies regarding to deep-ploughing and subsoiling were focused on the variations of grain yield in response to different technical rules and matched machine types. Yet, a long-term evaluation on soil water dynamics under these techniques is sorely missing. Furthermore, the relative yield increases due to deep-ploughing and subsoiling are greatly affected by rainfall distribution during both fallow and growing seasons, a long-term exploration on annual variation of grain yield and soil water storage under deep-ploughing and subsoiling is needed to clarify the rainfall influences on validity of both tillage methods. To narrow these knowledge gaps, a 7-year filed experiment was established in semiarid southeast of the Loess Plateau to exam the effectiveness of three tillage methods (i.e. deep ploughing, subsoiling and no-tillage) on water storage and wheat yield performance. The objectives of this study were: 1) to test and compare overall effects of tillage methods on temporal changes of soil water storage in the 0–300 cm layer during both fallow and growing seasons; 2) to analyze the spatial dynamics and annual changes of soil water storage in the 0–300 cm layer at three critical wheat developmental stages, 3) to evaluate the overall effects and annual variation of tillage methods on yield and components, water use efficiency, water storage efficiency, crop water consumption and 4) to build the quantitative linkage between water storage efficiency during fallow season and yield output and water use efficiency.

Table 1
Brief description of experimental site in Wenxi, southeast Loess Plateau.

Item	Value
Longitude (N)	35.3°
Latitude (E)	111.3°
Altitude (m)	639
Mean annual air temperature (°C)	12.9 (The average of 1980–2010)
Mean annual precipitation (mm)	490.9 (The average of 1980–2010)
Maximum precipitation (mm)	93.3 (In August)
Minimum precipitation (mm)	4.6 (January)
Evaporation (mm)	1838.9
Sunshine hours (h)	2242
Frost-free period (d)	190
Major crops	Winter wheat, Summer corn
Soil organic content (g kg^{-1})	8.93
Total nitrogen (g kg^{-1})	0.69
Available nitrogen (mg kg^{-1})	36.92
Available phosphorus (mg kg^{-1})	18.16
PH	6.9

2. Methods and materials

2.1. Description of experimental site

A 7-year field study was established at the Wenxi Dryland Wheat Agriculture Station (35°20′N, 111°17′E), Shanxi Province of China between 2009 and 2015. The site represents the typical semiarid climate of Northeast Loess Plateau. Table 1 presented the brief description of this experimental site. Winter wheat is staple crop for the people lived in this area, which was usually planted in the early October. Rainfed agriculture is popular owing to scarce rainfall and unavailable irrigation condition. More than 60% rainfall fell in the fallow season, i.e. July to September. This unmatched rainfall distribution regarding to crop water consumption is main limiting factor for wheat production in this area.

2.2. Experimental design and field management

In this experiment, three different tillage methods in fallow season were designed as: 1) deep ploughing to 25–30 cm; 2) deep subsoiling to 30–40 cm and 3) no tillage in fallow season as control. In each year, previous wheat was harvesting in end of June. Thereafter, tall stubble (20–30 cm) was remained to reduce water evaporation and increase soil organic carbon for next season. In the 10th to 15th day after previous harvesting, three tillage methods were initiated by using two different ploughing machines. The detailed ploughing dates in each year can be found in Table 2. In later August, rotary tillage and land leveling were performed for planting preparation. All treatments were arranged in a randomized, complete block design with three replicates in each experimental season. Each plot was 50 m long and 6 m wide consisting of 30 rows of wheat spaced 0.2 m for all treatments. Before sowing, pure nitrogen, P_2O_5 and K_2O were applied at the rate of 150, 38 and 75 kg ha^{-1} respectively. For each season, a local wheat cultivar 'Hanyun20410' was used, and the drilling sowing was applied for each plat using a planting machine. The planting density was 315 × 10^4 plant ha^{-1}. The sowing date in each year was presented in Table 2. All plants