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In search of long-term sustainable tillage and straw mulching practices for a maize-winter wheat-soybean rotation system in the Loess Plateau of China

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ABSTRACT

Development of sustainable agronomic practices and increasing crop water use efficiency (WUE) under the realm of water scarcity and climate change have become the major focuses in the semiarid Loess Plateau region of China. This 7-yr (2001–2007) study investigated the effects of conservation tillage practices and residue management on crop yield, WUE, soil organic carbon (SOC), soil water storage, economic return, and determined the contribution of various environmental factors on crop WUE under a two-year cycle spring maize (*Zea mays* L.)-winter wheat (*Triticum aestivum* L.)-summer soybean (*Glycine max* L.) rotation cropping system. Treatments included conventional tillage (T) as control, conventional tillage followed by straw mulching (TS), no tillage (NT) and no tillage followed by straw mulching (NTS). Averaged over years and species, the overall crop yield was greatest under TS treatment, which was 17 9 and 5% significantly greater than NT, T and NTS treatments, respectively. Additionally, TS treatment resulted in comparable or greater crop WUE than other treatments starting from 2004. Soil moisture storage was not significantly affected by treatments but varied greatly across different soil depths throughout the growing season. Soil organic carbon was significantly increased by straw mulching treatments (NTS and TS) beginning at 2004. In all, NTS treatment provided the greatest economic return on a system basis. Our simulation modeling results indicated that biomass and net radiation are the most important factors in determining WUE in the semiarid Loess Plateau of China.

1. Introduction

The sustainability and resilience of Chinese agriculture have been greatly challenged by the rapid population growth and substantial economic development in recent years, particularly in the semiarid crop production regions of China. The Loess Plateau is a major agricultural region located in the northwest of China, with an average annual rainfall below 600 mm and a total area of 648,700 km^2 accounting for about 6.8% of Chinese territory (Shan, 1993). Like other dry regions in the world, water scarcity and climate change are the most important ecological factors limiting agricultural productivity (Zhang et al., 2014). A study by Deng et al. (2015) showed that during 1961–2010, the annual mean temperature on the Loess Plateau has increased at an average rate of 0.32 °C every ten years, which could cause significant increase in evapotranspiration and alteration of energy/carbon balance of terrestrial ecosystems. Meanwhile, Yan (2015) reported that annual precipitation in this region has declined at an average rate of 0.751 mm yr^{-1} during 1961–2014 and IPCC (Intergovernmental Panel on Climate Change) also found that the precipitation reduction could reach 5% per decade at certain recorded sites in the Northwest China during 1951–2010 (IPCC 2013). Thus, designing and developing sustainable cropping systems that can maintain productivity, better tolerate extreme weather conditions, and use production inputs (particularly water) more efficiently have become the major focuses in this region (Trumbore et al., 1996; Grace and Rayment, 2000; Midgley et al., 2004).

On a global scale, incorporating crop rotations with limited or no tillage have become very popular in cropping system studies. Riedell et al. (2013) found that maize (*Zea mays* L.)-soybean (*Glycine max* L.)-wheat (*Triticum aestivum* L.)/alfalfa (*Medicago sativa* L.) rotations with conservation tillage provided better soil health, seed yield, and kernel mineral concentration than maize monoculture. Likewise, Huang et al. (2003a) found that pea/millet (*Panicum miliaceum*)/maize/maize rotation with conservation tillage practices provided significantly improved crop WUE on the Loess Plateau. In an economic study, Katsvairo and Cox (2000) suggested that soybean–maize rotation with low chemical inputs and limited tillage could provide similar net economic return compared with conventional tillage. Although crop rotation and

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conservation tillage have long been known for their economic and ecological benefits, effects of integrating different tillage and crop residue retention practices on the system-based productivity and sustainability are less well known particularly in the semiarid Loess Plateau region of China (Shao et al., 2016; Zhang et al., 2016a). Furthermore, the mechanism and contribution of various environmental factors on crop WUE as well as their interaction with different management practices in the semiarid environment have rarely been systematically studied.

Thus, this study was conducted to (1) study the effects of different conservation tillage/crop residue retention practices and changes of relevant environmental factors on crop yield, WUE, SOC, soil moisture change, and economic return of a spring maize-winter wheat-summer soybean rotation system on the Loess Plateau; (2) employ path analysis to investigate the interplay and contribution of various environmental factors on crop WUE, which is of great importance to producers and researchers in this region.

2. Materials and methods

2.1. Site description

A 7-yr tillage × residual straw mulching study was conducted in a spring maize-winter wheat-summer soybean rotation system at the Qingyang Loess Plateau Research Station of Lanzhou University (35°39′N, 107°51′E; elevation 1298m) from 2001 to 2007. The average long-term annual temperature ranges from 8 to 10 °C. The minimum and maximum temperatures are 39 °C and −22.4 °C, respectively. Mean annual accumulated heat unit is 3446 ° days. The growing season for major warm-season crops extends from March to October for about 255 days with 110 frost-free days on average. Annual precipitation is between 480–660 mm, and average annual pan evaporation is 1504 mm. The dominant soil type is sandy loam with an average field water-holding capacity of 0.223 cm^3/cm^3 and permanent wilting point of 0.07 cm^3/cm^3 determined using methods described by Cassel and Nielsen (1986) and Colla et al. (2000).

2.2. Experimental design and crop management

This study was a randomized complete block design with four blocks and a factorial treatment structure (two tillage practices × two straw mulching practices; 4 blocks × 4 treatments = 16 plots). The entire experiment was conducted within a bulk field with each plot measured as 52 m^2 (4 × 13 m) in area. The distance between two adjacent blocks and plots was measured as two and one meter, respectively. Treatments were imposed on an existing maize-wheat-soybean rotation cropping system based on different tillage and residue management practices, including conventional tillage (T), conventional tillage followed by straw mulching (TS), no tillage (NT), and no tillage followed by straw mulching (NTS). Crop rotations started after a summer soybean production in 2001 and was designed as a spring maize-winter wheat-summer soybean cycle. Each cycle spans two years and was repeated three times for a total of six years (2001, soybean monoculture; 2002–2003, 2004–2005, 2006–2007, spring maize-winter wheat-summer soybean rotations).

Farmlands in the Loess Plateau region of China typically feature small size, steep slope, and long distance to primary highway and country road systems, thus, preventing the usage of large farm equipment (e.g. combine harvester) and greatly favoring human labor (Huang et al., 2003b; Shao et al., 2016). Farmers typically collect crop residues after harvest and either burn them in the field or use as animal feed or fuel for heating (Komarek et al., 2015). Very few farmers return crop residues back to the field as a way to improve crop productivity and soil health. Additionally, little scientific information relating to residue management is available for guiding the decision making processes of local farmers. In our study, we used hand planting or specially designed planters/drills for small-plot seeding. All plots were sampled and harvested by hand in accordance with common farming practices adopted by farmers in the local region.

All plots were managed similarly except for treatment practices. All crops were planted and harvested by hand except for winter wheat (different planters were used under conventional tillage and no-till treatments). For T and TS treatments, all plots were plowed at a 30-cm depth before each planting using a chisel plow followed by manual mixing, smoothening, and conditioning using hand tools (e.g. shovels, hoes, and rakes). Soils under NT and NTS treatments remained undisturbed throughout the experimental period. Within each crop rotation cycle, ‘Zhongdan NO. 2’ maize was hand-planted in early April at a seeding rate of 30 kg ha^{-1} (Pure Live Seed, PLS) with a row spacing of 0.40 m. Starter fertilizer (diammonium phosphate, 18-46-0) was applied by hand at a rate of 300 kg ha^{-1} at planting. Urea N fertilizer (46-0-0) was applied at a rate of 300 kg ha^{-1} when the majority of maize plants reached V6 development stage (Abendroth et al., 2011). Maize was harvested manually in September and the remaining stalks were removed from the field by hand (T and NT) or shredded into 15-cm long pieces using a corn stalk shredder and returned evenly back to the original plots (TS and NTS).

‘Xifeng NO.24’ winter wheat was planted in late September immediately after maize harvest using a ‘Jinniu 2BF’ no-till drill (Jinniu Manufacturing Co., Qingyang, Gansu Province, China) under no-till treatments (NT and NTS) or a Xingnong drill (Xiguan Manufacturing Co., Baoji, Shanxi Province, China) after tillage treatments (T and TS). The seeding rate was 187 kg ha^{-1} PLS with a row spacing of 0.15 m. Starter fertilizer (diammonium phosphate) was applied at a rate of 300 kg ha^{-1} below the seed using a fertilizer coulter attached to the drill. Urea fertilizer was surface-broadcasted by hand at a rate of 150 kg ha^{-1} at the green-up stage (Feekes 4–5; Miller, 1999). Wheat was hand-harvested in late June of the following year with 30-cm tall stubbles left in the field. Depending on treatments, stalks within each plot were either removed (T and NT) or returned back to the field after reaping (TS and NTS).

‘Fengshou NO.12’ soybean was planted manually at a rate of 15 kg ha^{-1} PLS with a row spacing of 0.25 m immediately after winter wheat harvest in late June or early July. Banded starter fertilizer (Calcium superphosphate, 0–26-0) was applied at a rate of 63 kg ha^{-1}. Hand harvesting of soybean was completed by late October. The remaining stalks were either removed (T and NT) or left in the field (TS and NTS) according to treatment. All plots were hand-weeded periodically throughout the growing season and a one-time broadcast application of 3 kg ha^{-1} a.i. of Triadimefon [1-(4-Chlorophenoxy)-3,3-dimethyl-1-(1H-1,2,4-triazol-1-yl)-2-butanone] was used in 2003 for an insect outbreak.

2.3. Data collection

2.3.1. Meteorological measurements

Meteorological data were recorded using a weather monitoring system installed at the center of the experiment field. Particularly, ambient air temperature and relative humidity were measured using a HMP-50 Probe (Campbell Sci., Inc. Logan, UT). Net radiation was measured by a net radiometer (CNR-I, Kipp and Zonen Inc., Saskatoon, Saskatchewan, Canada). Rainfall was recorded using a rain gauge (TE525MM, Campbell Sci., Inc. Logan, UT). All variables were measured every ten seconds and 30-min average values were stored by a CR5000 data-logger (Campbell Sci., Inc. Logan, UT).

2.3.2. Crop yield

At each harvest, maize, wheat and soybean samples were taken randomly from three quadrats within each treatment replicate away from the plot edges during maturity stage for calculating crop yield, measured as 0.76, 0.3 and 0.25 m^2, respectively. Sampling protocol for each crop was exactly the same as what was described in Section 2.2.