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Modelling the effects of conservation tillage on crop water productivity, soil water dynamics and evapotranspiration of a maize-winter wheat-soybean rotation system on the Loess Plateau of China using APSIM

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ABSTRACT

Information relating to the accurate quantification of the impacts of long-term conservation tillage practices on the crop yields and water use patterns of rainfed rotational cropping systems under global climate change is urgently required. The objectives of this study were to calibrate and evaluate APSIM (Agriculture Production System sIMulator) to accurately predict crop growth and development of a maize-winter wheat-soybean rotation, and to investigate the effects of conservation tillage on grain yield, water productivity and evapotranspiration on the Loess Plateau of China. This study integrated APSIM-based simulation modelling and field-level data collected from a maize-winter wheat-soybean rotation system under conventional tillage (CT) and no tillage with stubble retention of the previous crop (NTR) in Xifeng, Gansu, China. APSIM was successfully calibrated and evaluated using the root mean square error (RMSE) and index of agreement (d), indicating good performance on simulating the crop yield, dry matter biomass and soil water dynamic of the three crops for both CT and NTR treatments. Under the long-term scenario simulations (50 a, 25 rotation phases in total), the results showed that NTR improved soil water storage by 0–159 mm (72 mm on average; $P < 0.01$) of soil water storage before each rotation phase. The grain yield and biomass of winter wheat were significantly improved under the NTR treatment (1805 and 4309 kg ha^{-1} on average), but changes in maize or soybean were not significant ($P > 0.05$). On a system basis, the NTR treatment had significantly greater plant transpiration (T_c) and T_c/system water supply (WS_{sys}), but lower soil evaporation (E_s), evapotranspiration (ET), and ET/WS_{sys} than treatment CT did. Additionally, T_c and E_s for maize production were not significantly different between the two treatments. Grain yield water productivity (WP_Y) and biomass water productivity (WP_B) in wheat and soybean were substantially improved by 1.9–8.0 kg ha^{-1} mm^{-1} ($P < 0.05$) under treatment NTR. In general, we advocated that conservation tillage has indicated great potential for improving crop/water productivity and soil water storage under rainfed conditions in the semiarid Loess Plateau region of China.

1. Introduction

Conservation tillage is defined as any agricultural practice that aims to conserve soil moisture and reduce soil erosion by leaving soil surface covered by crop residues and/or subsoil less disturbed (Fowler and Rockström, 2001). Common conservation tillage practices, including no tillage, subsoil tillage, reduced or shallow tillage, subsoil tillage with straw mulching/retention, etc., have been adopted in many regions around the world (Awada et al., 2014; Xie et al., 2016). Previous research has indicated that conservation tillage could mitigate the effects of dry spells (Barron et al., 2003), increase crop productivity (Awada et al., 2014), and improve the improve physical, chemical, and biological properties of soil (Singh et al., 2005). Thus, there has been increased attention on incorporating conservation tillage practices into conventional management practices in recent years. Yield advantages observed under conservation tillage in the arid/semiarid environments were mainly attributed to reduced water loss, improved soil water holding capacity, and enhanced nutrient availability (Martinez et al., 1995; Busari et al., 2015; Nyakudya and Stroosnijder, 2015). Improved crop water productivity (WP) was also reported across various

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agroecosystems globally (Barron et al., 2003; Su et al., 2007; Liu et al., 2013). However, some studies noted that neither no tillage nor straw mulching could actually increase crop yield (Mupangwa and Jewitt, 2011; Pittelkow et al., 2015; Ernst et al., 2016). Furthermore, Strudley et al. (2008) and Lal et al. (2004) summarized that conservation tillage could cause soil compaction and reduce infiltration of soil water. Therefore, the effects of conservation tillage on crop production depend greatly on many environmental and ecological factors, and obtaining site-specific data is essential for predicting/estimating agronomic productivity and ecological consequences on a system level.

The Loess Plateau is a quintessential dry-land agronomic region of China, where the intensity and duration of solar radiation and the diurnal temperature variation provide suitable environmental conditions for the production of many dry-land or water-conserving crop species/varieties in the nation. Precipitation is the main water input and the most limiting factor for crop production in this region (Shan and Chen, 1993). Annual precipitation of the Loess Plateau region ranges from 200 to 750 mm, with approximately 70% of precipitation occurring from June to September often in the form of heavy or scattered thunderstorms. Meanwhile, the quantity and distribution pattern of precipitation have changed dramatically in the past decade, posing great challenges for successful crop production in this region. In particular, the increased incidence of extreme weather events such as prolonged droughts and intense rainstorms has been observed more often in the most recent years (Ren et al., 2018), leading to increased severity of soil crusting and erosion, causing significant nutrient loss, compromised soil structure and reduction of soil fertility (Mueller and Pfister, 2011). Therefore, if the productivity and ecological function of the Loess Plateau region are to be sustained, new managerial practices that are less consumptive of farming inputs and natural resources such as conservation tillage practices are essential. Previous studies have focused on the effect of using conservation tillage in continuous monoculture cropping systems in semiarid regions of the Loess Plateau (Su et al., 2007; Zhang et al., 2014; Xie et al., 2016). However, information relating to the effects of conservation tillage on predominant rotational cropping systems [for example, maize (*Zea mays* L.)- winter wheat (*Triticum aestivum* L.)- soybean (*Gyleine* max L.) rotations] from a long-term view, is limited.

Process-based crop models are frequently used as a scientific tool to investigate the impacts of changes in managerial and environmental factors on crop production. The APSIM (Agriculture Production System sIMulator) framework is one of the most widely used process-based models for simulating crop production, risk management, and crop adaptation under various cropping system studies (Keating et al., 2003; Singh et al., 2011; Archontoulis et al., 2014a). By linking of crop growth with soil hydrological processes, APSIM has been successfully used to predict the productivity of many crop species, including maize (Archontoulis et al., 2014b), wheat (Bassu et al., 2009), soybean (Archontoulis et al., 2014a), and several other agronomic crops (Chen et al., 2008; Masikati et al., 2014). However, information relating to modelling rotational multispecies systems remains limited.

Taken together, there is an urgent need to accurately quantify and model the effects of conservation tillage practices on the yield and water use pattern of the maize-winter wheat-soybean rotation systems on the Loess Plateau of China. In this study, we integrated APSIM-based simulation modelling and long-term field data from a maize-winter wheat-soybean rotation system to: 1) calibrate and evaluate APSIM for accurately predicting crop growth and development of a maize-winter wheat-soybean rotation system under conservation or conventional tillage practices; 2) investigate the effects of conservation tillage on the soil water content, grain yield, and water productivity of the three crops under projected weather condition; and 3) evaluate the effects of conservation tillage on evapotranspiration at the system scale.

2. Materials and methods

2.1. Experimental site

The field experiment component of this study was conducted at the Qingyang Loess Plateau Research Station of Lanzhou University (35°40′N, 107°52′E; altitude 1298 m) in Xifeng, Qingyang City, in Gansu Province of China (Fig. S1). Agriculture in this area is mainly rainfed with a semiarid climate featuring predominant summer precipitation as well as dry and cold winter seasons (BSk in the Köppen climate classification; Peel et al., 2007). The average annual precipitation is 546 mm, with an average of 255 frost-free days per year. The mean annual temperature ranges from 8 °C to 10 °C, and the mean annual total sunshine hours ranges from 2300 to 2700 h. The soil is classified as Heilu (a very deep loess sandy loam of the Los Orthic Entisols based on the FAO soil classification; FAO, 1990). The groundwater depth is below 50 m. The weather data, including daily maximal and minimal air temperature, daily precipitation and daily solar radiation, was obtained from the Meteorologic Bureau of Xifeng (the distance between the meteorological station and the experimental site is 19.6 km).

2.2. Experimental design

During the seven growing seasons (2001–2007, meanwhile the seventh maize, winter wheat and soybean seasons were harvested in 2007, 2008 and 2007, respectively; Fig. S2) of a maize-winter wheat-soybean rotation, the effects of two tillage treatments were continuously investigated, including conventional tillage (CT treatment) and conservation tillage (no tillage with previous crop's stubble retention; NTR treatment). Each treatment was replicated four times in a randomized complete block design with a total of 16 plots. Each plot was 52 m^2 (4 m × 13 m) in area. There were 2-m spaces between adjacent blocks and 1-m spaces between adjacent plots. Maize was sown in late April and harvested in late September, followed by winter wheat, which was harvested in the early July of the next year. After winter wheat harvesting, soybean was planted and generally harvested in late October. There were two separate sequences of rotations both initiated in 2001 (Fig. S2).

Soil was plowed to a 20-cm depth before sowing and after harvesting of each crop in the CT treatment, whereas no tillage was used for the NTR treatment throughout the growing seasons. All three crop's residues were harvested, ground or cut into 5–10 cm fragments. For the NTR treatment, all soybean and wheat residues and 50% of the maize residues within each plot were returned back to the field. This practice closely mimics the traditional local labor-intensive farming methods in China, which involve very little usage of large farming equipment such as combine harvesters. Farmers typically harvest maize and soybean by hand and feed stubble to livestock or use them for winter heating and cooking purposes. There is a very small portion of farmers who incorporate straw mulching into their predominant management practices.

The cultivars and seeding rates for all three crops used in this study were 'Zhongdan2' at 30 kg ha^{-1} (6.93 plants m^{-2}), 'Xifeng24' at 187 kg ha^{-1}, and 'Fengshou12' at 15 kg ha^{-1}, for maize, winter wheat, and soybean, respectively. All crops were sown using a small no-till seeder (5–6 rows at a1.2-m width) designed by the China Agricultural University. For maize, 54 kg N ha^{-1} and 60.3 kg P_2O_5 ha^{-1} and 138 kg N ha^{-1} was applied before planting and at the booting stage (Feekes' scale 8), respectively. For winter wheat, the fertilizer application at sowing was 54 kg N ha^{-1} and 60.3 kg P_2O_5 ha^{-1}, and 69 kg ha^{-1} N was applied at the jointing stage (Feekes' scale 6). For soybean, a one-time application of 27.7 kg ha^{-1} of P_2O_5 was added. Weeds in all plots were removed periodically by hand, and no irrigation water was supplied throughout the growing season in each year.

Grain yield and dry matter biomass of three crops were determined