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Developing sustainable cropping systems by integrating crop rotation with conservation tillage practices on the Loess Plateau, a long-term imperative

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ABSTRACT

Loess Plateau agriculture, largely dependent on manual labor and precipitation water, exemplifies semiarid dryland agricultural systems in China, where better cropping systems and practices are essential for maintaining crop productivity and sustaining natural resources. An 11-year (2001–2011) study at the Xifeng, Gansu investigated the effects of different conservation tillage practices and straw mulching methods on yield, water productivity (WP), soil organic carbon (SOC), total nitrogen (TN), energy expenditure and economic returns of a maize (*Zea mays* L.)-winter wheat (*Triticum aestivum* L.)-summer soybean (*Glycine max* L.) rotation 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). On average, TS treatment had increased yield by 11, 22, and 4%; as well as WP by 13, 22, and 7% than T, NT and NTS treatments, respectively. Additionally, NTS indicated the greatest effect in increasing SOC and TN in the 0–10 cm soil layer. Our support vector machine (SVM)-based simulation modeling indicated great performance on predicting maize yield (R^2 = 0.76) and wheat WP (R^2 = 0.84) based on a 10-fold cross validation (10-fold CV). TS treatment provided the greatest net energy and net economic income, and NTS treatment indicated the greatest economic benefit.

1. Introduction

To meet the growing demand for food abundance and security in the fast-growing developing countries as China, and at the same time maintain the social, economic, and environmental sustainability across different agroecosystems, agricultural innovations and integrated system approaches are imperative. The Loess Plateau is one of the most intensive agronomic production regions in China featuring large grain-crop acreage, limited precipitation, erratic weather condition, and severe environmental degradation (Shan, 1993). To address the societal, ecological, and agricultural concerns on how the increasing population can be sustained, tremendous amount of alternative/innovative production practices have been adopted by producers nationwide, including rotational cropping and conservation tillage (Li et al., 2007; Wang et al., 2009; Liu et al., 2014b; He et al., 2016; Niu et al., 2016; Lu and Lu, 2017). Particularly, conservation tillage/rotation practices, characterized by minimized soil disturbance, incorporation of straw mulching and integrated crop rotation (especially using legumes) have accounted for 6.67×10^7 ha of the agricultural acreage in China (Kassam et al., 2015).

A large number of studies have shown that conservation tillage practices have produced favorable ecological benefits, including improved soil structure, increased soil organic contents, reduced surface runoff and soil erosion, improved nutrient condition of soil as well as increased crop yield and water use efficiency (Tabaglio et al., 2009; Mazzoncini et al., 2016; Somasundaram et al., 2017). Meanwhile, there are clear evidences that incorporating straw mulching in conservation tillage practices could reduce greenhouse gas emission by tillage, save production costs, and further increase profitability (Sharma et al., 2011; Jin et al., 2017; Lu and Lu, 2017). However, great amount of heterogeneity also exists in productivity and economic impact due to the fact that many crop varieties and indigenous practices have been spatially and temporally compartmentalized, which greatly hinder the interpretation and conclusion of certain experimental effects related to conservation practices. For example, many studies have also indicated that neither zero tillage nor straw mulching could actually increase

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crop yield or profitability (Pittelkow et al., 2015; Ernst et al., 2016; Seddaiu et al., 2016). Therefore, obtaining site-specific results is essential.

The Loess Plateau is located in the semi-arid climate zone of northwestern China. The prevalence of traditional tillage and labor-intensive farming has fed millions of people for thousand years, meanwhile, has significantly overburdened the ecological resilience and sustainability. Nowhere is more evident than in the semi-arid Loess Plateau of China where information related to alternative farming practices and long-term studies is extremely lacking. Only a few long-term studies have been conducted on agricultural innovation and sustainable farming practices such as conservation tillage and crop rotation. For instance, the 15-yr research conducted by Li et al. (2007) on the eastern Loess Plateau showed that the zero tillage and straw mulching improved soil structure, soil fertility, crop yield and water use efficiency. In another study, Wang et al. (2009) suggested it would take at least seven years before crop yield and soil health effects related to conservation tillage treatments can be detected.

Meanwhile, the profitability associated with conservation tillage was doubled compared to traditional tillage by the end of the experimental period. Liu et al. (2014b) found that the long-term use (> 17 yr) of zero tillage significantly increased the concentration of various fractions of soil organic carbon and raised the grain yield of winter wheat on the Loess Plateau. A five-yr study conducted by He et al. (2016) showed that the straw mulching has increased soil water content and evapotranspiration yet would not improve the crop yield. Likewise, in another research on maize-winter wheat-rotation system carried out by Li et al. (2018) found that zero tillage incorporated with straw mulching provided similar grain yield but better economic profitability compared with conventional tillage without straw mulching.

Without question, the future of agriculture in this region depends on more long-term research work as well as scientific evidence and data availability. Advanced analytic tools, such as simulation modeling, are warranted to provide better understanding of current data and enable great predictability of future outcomes on much larger scales. Modeling agronomic and ecophysiological processes in a highly coupled manner could provide important insights in understanding how different residual management practices and environmental conditions could impact crop production (e.g. grain yield and water productivity; Luo et al., 2011; Schipanski et al., 2014; Basche et al., 2016). It can also help to address the spatial and temporal variability nature of agronomic data by upscaling simulated results to a much larger regional or decadal scale.

Information abounds with using various existing process-based models in agronomic research, such as Agricultural Production Systems Simulator (APSIM), STICS crop model, Decision Support System for Agrotechnology Transfer (DSSAT), Erosion Productivity Impact Calculator (EPIC), etc. (Salmerón et al., 2014, Yeo et al., 2014, Plaza-Bonilla et al., 2015). However, almost all of these existing models require significant effort on parameter calibration and are heavily dependent on simple mathematical algorithms such as linear regression, thus, can easily cause model overfitting, poor robustness, and low accuracy (Cui et al., 2014a,b, Mirik et al., 2014a,b). In this study, we used one of the state-of-the-art machine learning algorithms (support vector machine, SVM; Boser et al., 1992; Cortes and Vapnik, 1995; Cui et al., 2014a,b; Lin et al., 2018; Ramcharan et al., 2018) and implemented novel site-specific models that have provided accurate results, which could lead to deeper understanding on the impacts of different environmental conditions and managerial practices on crop productivity. It was noteworthy that the proposed modeling paradigm could be easily adapted to other studies under different cropping systems or environmental conditions.

Although crop rotation, conservation tillage, and straw mulching have long been known for their individual agricultural benefits, synergized effects involving all three management regimes coupled with simulation modeling on a long-term basis is less well-known. In this study, we researched the influences of different conservation tillage and straw mulching practices on (1) crop productivity (grain yield and water productivity), (2) soil health and nutrient status (soil moisture, SOC, TN); (3) economic benefits and fossil fuel use of a multi-sequence long-term (10 yr) spring maize-winter wheat-soybean rotation system on the semiarid Loess Plateau. Additionally, we also (4) investigated the potential of using SVM for constructing site-specific prediction models as well as determining the contributions of environmental and managerial factors on grain yield and water productivity on a cropping system basis.

2. Materials and methods

2.1. Site, experimental design and crop management

This 11-yr experiment was started in 2001 at the Qingyang Loess Plateau Research Station of Lanzhou University (35°39′N, 107°51′E; elevation 1298 m) in Northwestern China from 2001 to 2011. The growing season for major crops extends from March to October for about 255 days with 110 frost-free days on average. Annual precipitation is between 480 and 660 mm and more than 60% falling from July to September (Fig. 1). Average field water-holding capacity is around 0.223 $cm^3 cm^{-3}$ and permanent wilting point is 0.07 $cm^3 cm^{-3}$. The predominant soil type is sandy loam and the climate is semiarid with very dry summer and harsh winter conditions which would not favor soil organic matter accumulation. The primary agronomic production in the Loess Plateau region of China features small-scale and heavy dependency on hand labor input. Farmers typically collect crop residues after harvest and either burn them in the field or use them as animal feed or fuel for winter heating purposes. Very few farmers return crop residues back to the field as a way to improve crop productivity and soil health. Additionally, many farm lands in the Loess Plateau region are fairly small and feature complex topographical challenges (e.g. steep slope) for using large farming equipment. Therefore, human labor-based intensive practices such as hand planting, harvesting, as well as hand weeding in conjunction with very little dosing of herbicide are common.

Before this study was implemented in 2001, the same field was used for an intensively-tilled continuous maize monoculture system for many years followed by a three-year-no-cover fallow period used for preserve soil moisture. This experiment was set up as a randomized complete block with split-plot treatment design replicated four times. Treatments also had a factorial structure arrangement, thus, the study included two sequences (whole-plot factor) × four blocks × two tillage practices (split-plot factor) × two straw mulching practices (split-plot factor) = 32 plots. The entire experiment was conducted within a bulk field with each plot measured as 52 m^2 (4 × 13 m) in area. A detailed layout of the entire field was presented in Fig. S1. Treatments were imposed on two existing maize-wheat-soybean rotation cropping systems based on different tillage and straw 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 spring maize (sequence 1) and summer soybean (sequence 2) production in 2001 and was designed as a two-yr spring maize-winter wheat-summer soybean cycle (Table 1). Each cycle spans two years and was repeated five times (five phases in each sequence) for a total of ten years (Table 1).

In our study, three crops were planted by manual no-tillage machine which was a specially planters/drills for small-plot seeding designed by China Agricultural University. All plots were sampled and harvested by hand in accordance with common farming practices adopted by local farmers. All plots were managed alike except for assigned treatments. For both T and TS treatment plots, a 30-cm-depth chisel plow was used before each planting followed by manual smoothening using hand tools (e.g. shovels, hoes, and rakes). Soils under the NT and NTS treatment plots were kept undisturbed during the entire experimental period.