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FIELD-SCALE SIMULATION OF WINTER-WHEAT LEAF AREA INDEX, SOIL MOISTURE AND WATER-USE EFFICIENCY IN WEST HENAN, CHINA

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Crop growth simulation models are useful in evaluating the impacts of different tillage and residue management operations on the changes in land productivity and soil-water balance components. We applied the new Decision Support System for Agro-technology Transfer (DSSAT) version 4.5, an improved crop growth simulation model, to three conservation agriculture treatments and one conventional tillage treatment data from a field-scale study in the west Henan region of China to predict winter-wheat yield, leaf area index and soil-water balance. The area has a winter wheat-fallow-winter wheat rotation with winter wheat planting in October and harvesting in June. The model was calibrated using 2005-2006 winter-wheat crop data from field experiments of four treatments. The DSSAT satisfactorily simulated the treatment variations in winter-wheat yield, leaf area index and soil-water balance. There was good agreement between observed and predicted yields. Although the results show that the DSSAT V4.5 is well suited for simulating winter-wheat growth in the West Henan region of China, these results are preliminary and based on only one year of experimental data and four treatments. Further long-term analyses need to be carried out for improving the understanding of the conservation agriculture cropping systems in the west Henan region of China.

INTRODUCTION

Crop growth simulation models can be useful in evaluating the impacts of different tillage and residue management operations on the changes in land productivity and soil-water balance components. Compared to field experiments, the use of crop models to evaluate crop responses to a wide range of management and environmental scenarios can give more timely answers to many management questions at a fraction of the cost of conducting extensive field trials. As a result, a wide range of crop models such as APSIM (Agricultural Production Systems sIMulator; McCown et al., 1996), CropSyst (Cropping System Simulation Model; Stöckle et al., 2003), DSSAT (Decision Support System for Agro-technology Transfer; Jones et al., 2003), EPIC (Erosion Productivity Impact Calculator; Williams et al., 1989), NTRM (Nitrogen-Tillage-Residue Management; Shaffer and Larson, 1987) and PERFECT (Productivity Erosion and Runoff Functions to Evaluate Conservation Techniques; Littleboy et al., 1989,1999) have been developed and are being used to evaluate the impact of agricultural management practices. Conservation agriculture is the application of a set of four principles including reduced or zero tillage, residue retention, crop rotation and cover crops applicable to the local conditions to develop rational management of soil disturbance, residues, and rotation, and economic benefit. Simulation models offer a potentially valuable set of tools for examining questions related to performance of conservation agriculture. This can be both to improve our understanding or conceptualization of processes and to improve quantitative predictions for use by agronomists, growers, policy makers or others. The DSSAT was originally developed by an international network of scientists, cooperating in the International Benchmark Sites Network for Agro-technology Transfer project (IBSNAT, 1993; Jones et al., 1998; Tsuji, 1998; Uehara, 1998), to facilitate the application of crop models in a systems approach to agronomic research. Many scientists using and developing DSSAT have been able to integrate field research results and test the model for: 1) the effect of soil-water balance and water stress on winter-wheat production under different climate change scenarios in Austria (Eitzinger et al., 2003); 2) analyze effects of crop residue and nitrogen effects on rice-wheat rotation in Kharagpur, India (Reshmi and Sandipta, 2008) and 3) evapotranspiration and soil-water balance in southern Spain (Sau et al., 2004).

Most DSSAT applications in China have used an older version (version 4.0 or older) (Zhang et al., 2004; Zhao, 1999; Lei, 2000; Li et al. 2001b,c, 2002) of DSSAT which was not capable of simulating the influence of tillage and residue cover on soil properties and plant development. In this study, we calibrated an improved version of DSSAT (version 4.5) at field scale using the four different tillage treatments data collected in the west Henan region of China. Our objectives were: (1) to calibrate the improved DSSAT for plant and soil parameters using field experiments and (2) to simulate, quantify and explain field scale changes in leaf area index (LAI), soil-water balance and water-use efficiency with different tillage treatments.

The results presented here are based on preliminary investigations over a one year time period and a four tillage treatment dataset. We intend to continue studying the effects of conservation agriculture on the long-term changes in the soil-water balance and yield.

MATERIALS AND METHODS

Site description and experiment design

The field site was located in Songzhuang village of Mengjin County in the western region of Henan Province, China (N 34 ° 43'-34 ° 57'; E 112 ° 12'-112 ° 49'; 130m above mean sea level,

Figure 1). The climate of Mengjin County is described as temperate zone continental monsoon, characterized by cold winters, spring droughts and high rainfall in the summer and autumn. Over the past 36 years (1971-2006), the mean annual rainfall has been 632mm and the mean annual temperature 14°C (Table 1). It is a hilly region with high frequency of drought and serious soil erosion. The water table at the site is about 20m below the soil surface.

A continuous winter-wheat crop is grown with a fallow period during summer months each year. The study included four treatments. The first was decreased tillage (DT), in which 10-15cm height wheat straw was left at harvest and the rotary hoe was used to till to a depth of 25cm. It was carried out on July 1 after the winter-wheat was harvested. The second treatment was zero tillage (ZT) in which there was no tillage operation and a winter-wheat straw of 35-40cm height was left after wheat harvest. The third treatment was subsoiling (SS) in which wheat straw of 35-40cm height was left when winter-wheat was harvested and the field was tilled to 40cm depth by wheelless subsoiler on July 1. The fourth treatment was conventional tillage (CT). In this treatment wheat straw of 10-15cm height was left in the field when winter-wheat was harvested and two tillage operations - on July 1 and September 2 - were carried out. The rotary hoe was used and tillage depth was 25cm. Three replicates of each treatment were randomly distributed in the field. The size of each plot was 90 m^2. Winter-wheat cultivar Luohan No.06 was sown on October 1 (225 $kg \cdot ha^{-1}$) and urea was applied (105 $kg \cdot ha^{-1}$, N: P: K=1:0.38:0.25).

Field measurements

During the experiment period, soil-water content was measured at depths of 5, 15, 30, 45, 60, 90 and 120cm, twice per month, and once after every rainfall event.

LAI was measured manually at irregular intervals 5 to 6 times during the growing seasons using at least 10 adjacent plants on each occasion. Leaf area was calculated by multiplying leaf length by the greatest width and a correction factor (0.79) estimated from leaf area measurements. The sum of all the green leaf areas was used to determine LAI based on the number of plants in the plot. The biomass and grain yield were measured by manually harvesting each plot.

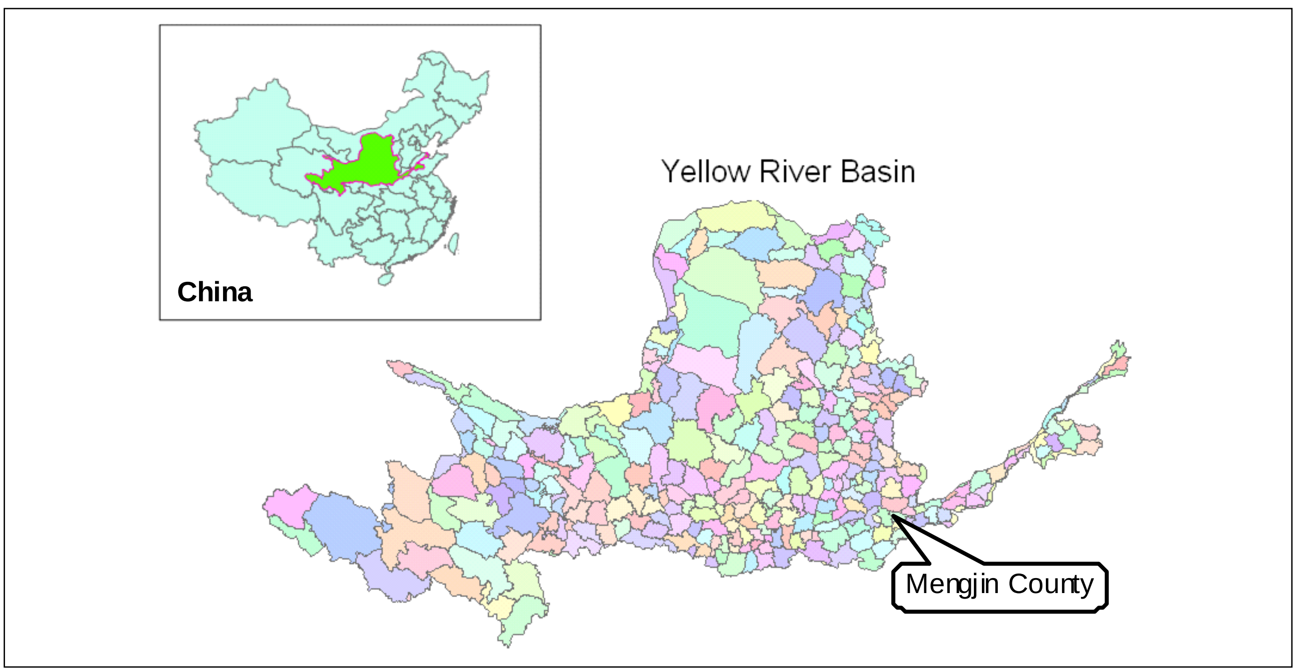

Figure 1. Location of Mengjin County in the Yellow River Basin.

Model description

DSSAT is a package which incorporates CROPGRO and CERES crop growth models. The CERES-wheat model is used to simulate wheat cultivation. A detailed description of the CERES models can be found in Ritchie et al. (1998a). They can predict the growth duration, average growth rates and the amount of assimilate partitioned to the economic yield components of the crop. The soil water balance in DSSAT is based on Ritchie's model, where the concept of upper and lower drained limits of soil water is used as a basis for the available water in the soil (Ritchie 1981a,b). In our simulations, the modified Priestly-Taylor method is used to estimate evapotranspiration. We used the DSSAT version 4.5 which includes the new tillage model based on the improved CERES-Till (Dadoun, 1993) - a model used to predict the influence of crop residue cover and tillage on soil surface properties and plant development. CERES-Till has been tested for maize and has demonstrated the ability to simulate differences in soil properties and maize yield under several tillage systems. Andales et al. (2000) have improved the CERES-Till model and now the model accounts for residue incorporation and its effects on the soil nutrient balance as well as water balance and on soil temperature. The model has provisions for the input of tillage date, tillage implement, and tillage depth and it accounts for changes in soil physical properties (bulk density, hydraulic conductivity, porosity, surface residues and soil temperature) caused by tillage. A detailed description of the improved CERES-Till model can be found in Andales et al. (2000).

Model application

The DSSAT needs to be set up for three standard modules for controlling a simulation run-weather module, soil module and plant module.

The main function of the weather module is to read or generate daily weather data. It reads in daily weather values - maximum and minimum air temperatures, solar radiation and precipitation, solar radiation, relative humidity and wind speed (when available). The 2005-2006 weather data were downloaded for the county weather station from the Chinese national weather service website (http://cdc.cma.gov.cn). Table 1 presents monthly temperature total precipitation for the simulation period.

Table 1. Long-term average (1971-2006) weather data for Henan experimental site and precipitation data for 2005-2006.

Month	---------Long term Average---------		2005	2006
	Temperature	Precipitation	Precipitation	Precipitation
	(?)	(mm)	(mm)	(mm)
January	0.1	8.8	0.0	25.8
February	2.7	12.2	8.3	17.8
March	8.0	28.5	9.6	5.4
April	15.5	39.6	13.3	37.0
May	21.0	58.0	56.5	65.5
June	25.7	62.8	132.9	82.9
July	27.0	155.5	214.4	181.9
August	25.6	112.5	118.0	162.1
September	21.0	77.4	133.3	50.0
October	15.1	45.1	35.3	0.0
November	8.0	22.3	4.9	58.7
December	2.2	9.8	2.3	5.5
Yearly Total		632.4	728.8	695.6

Soil properties such as hydraulic conductivity and soil water retention curves were used as model input to the soil module. All of the soil data were acquired from Chinese Soil (Beijing, 1995) and Henan Soil (Beijing, 2004) surveys. Table 2 describes the soil properties used in setting up the DSSAT model.

Table 2. Soil initial conditions used for the DSSAT simulations.

Depth (cm)	Saturated hydraulic conductivity ($cm \cdot h^{-1}$)	pH	Bulk density ($g \cdot cm^{-3}$)	Clay	Silt	Sand	Drained upper limit	Drained lower limit
				----------(%)----------			----------(mm)----------	
0? 5	0.61	7.8	1.39	17.6	37.8	44.6	0.26	0.14
5? 15	0.52	8.1	1.43	17.2	32.6	50.2	0.25	0.13
15? 30	0.43	8.0	1.43	16.8	33.2	50.0	0.25	0.13
30? 45	0.43	8.1	1.44	16.2	33.4	50.4	0.24	0.12
45? 60	0.43	8.3	1.45	18.5	33.1	48.4	0.25	0.13
60? 90	0.42	8.2	1.47	21.9	32.8	45.3	0.26	0.14
90? 120	0.42	8.2	1.48	22.3	31.6	46.1	0.26	0.14

Genetic coefficients are used to depict crop varietal characteristic, control the course of growth, stage of plant and formation of yield of crops. Chinese Loess Plateau (Li et al., 2001a) is a database of individual crop varietal genetic coefficients. According to this database and conversion from V3.5 to V4.0 of DSSAT (Hoogenboom, 2004), the genetic coefficients of winter wheat cv. Luohan No.06 were estimated.

Analytical method

The field water balance can be written as

$$P=E+T+R+D+\Delta S-I \quad (1)$$

where P is precipitation, E is soil evaporation, T is crop transpiration, R is surface runoff, D is drainage, ΔS is the change in soil water storage and I is irrigation. In this study, no irrigation was applied.

Water use efficiency (WUE) was defined as

$$WUE = \frac{Y}{ET} \quad (2)$$

Where WUE represents water use efficiency for the grain yield ($kg \cdot ha^{-1}$), Y is the grain yield of the winter wheat and ET is the evapotranspiration during the winter wheat growth period.

This study uses the root mean square error (RMSE) to test the error between simulated and measured values. The expression of RMSE is

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(p_i - o_i\right)^2} \quad (3)$$

where p_i is model simulated value, o_i is measured value and n is total number of data.

RESULTS AND DISCUSSION

Model parameterization and calibration

Model calibration was conducted following the procedure outlined by Hu et al. (2006). We modified the varietal coefficients one at a time to check sensitivity of output to their change. The study searched for optimum values of the varietal coefficients in increments of 5% between specific lower and upper bounds, based on literature and default values available. Table 3 lists the final values of the varietal coefficients for the Luohan No.06 variety of winter-wheat.

Table 3. Genetic coefficients for the winter wheat cv. Luohan No.06.

No.	Parameter	Meaning	Value
1	P1V	Vernalization sensitivity coefficient (%/d of unfulfilled vernalization)	60
2	P1D	Photoperiod sensitivity coefficient (% reduction/h near threshold)	75
3	P5	Thermal time from the onset of linear fill to maturity (? d)	500
4	G1	Kernel number per unit stem? /spike weight at anthesis (#/g)	30
5	G2	Potential kernel growth rate (mg/(kernel d))	40
6	G3	Tiller death coefficient. Standard stem? spike weight when elongation ceases (g)	1.5
7	PHINT	Thermal time between the appearance of leaf tips (? d)	95

The model was used to predict the grain yield at harvest for all four treatments during the cropping seasons of the experimental period 2005-2006. Table 4 lists the values and their respective prediction differences. The analysis shows that the error absolute values were less than 3.94%, the error mean absolute value was 2.78%, and the model described the differences between the treatments consistently, similar to the measurements. The simulated winter wheat yield of four tillage treatments showed very good agreement with the measured values.

Table 4. Comparison between measured and simulated winter wheat crop yield results for four treatments.

Treatment	Measured	Simulated	Error
	--------Kg·ha^{-1}--------		%
DT	4970	5166	-3.94
ZT	5412	5216	3.62
SS	5477	5445	0.58
CT	5023	5172	-2.97

Leaf area index (LAI)

The simulated LAI agreed well with field measurements from 1st October 2005 to 1st June 2006, as shown in Figure 2. The simulation of subsoiling (SS) LAI (Figure 2c, RMSE=0.297, r^2=0.993) was best amongst the four treatments, the RMSE of other simulations and measures were also very small; the RMSE of decrease tillage (DT) was 0.387, the RMSE of zero tillage (ZT) was 0.591, and the RMSE of conventional tillage (CT) was 0.367. The shape of the curve indicated the enhanced version of DSSAT satisfactorily simulates the LAI development for winter wheat in west Henan.

Simulated water balance components

Soil water storage

The total soil water storage for the depth 150cm soil profile was similar for all treatments. Therefore, this paper uses DT and ZT treatments as examples to show the soil-water change. The maximum rooting depth of winter wheat is generally about 20-45cm. So, soil layers of thickness 5-15, 15-30 and 30-45cm are important for simulating correct winter-wheat plant water uptake and thus the soil water balance. Soil water dynamics in the surface soil layers are difficult to model due to high spatial and temporal variations in organic matter contents, macropores, and other properties. As seen in Figures 3 and 4, the RMSE is relatively small for these layers compared to the top layer (0-5cm) and deeper layers. Similarly, soil moisture values were compared for two other treatments (SS and CT) and there was similar satisfactory agreement between the model

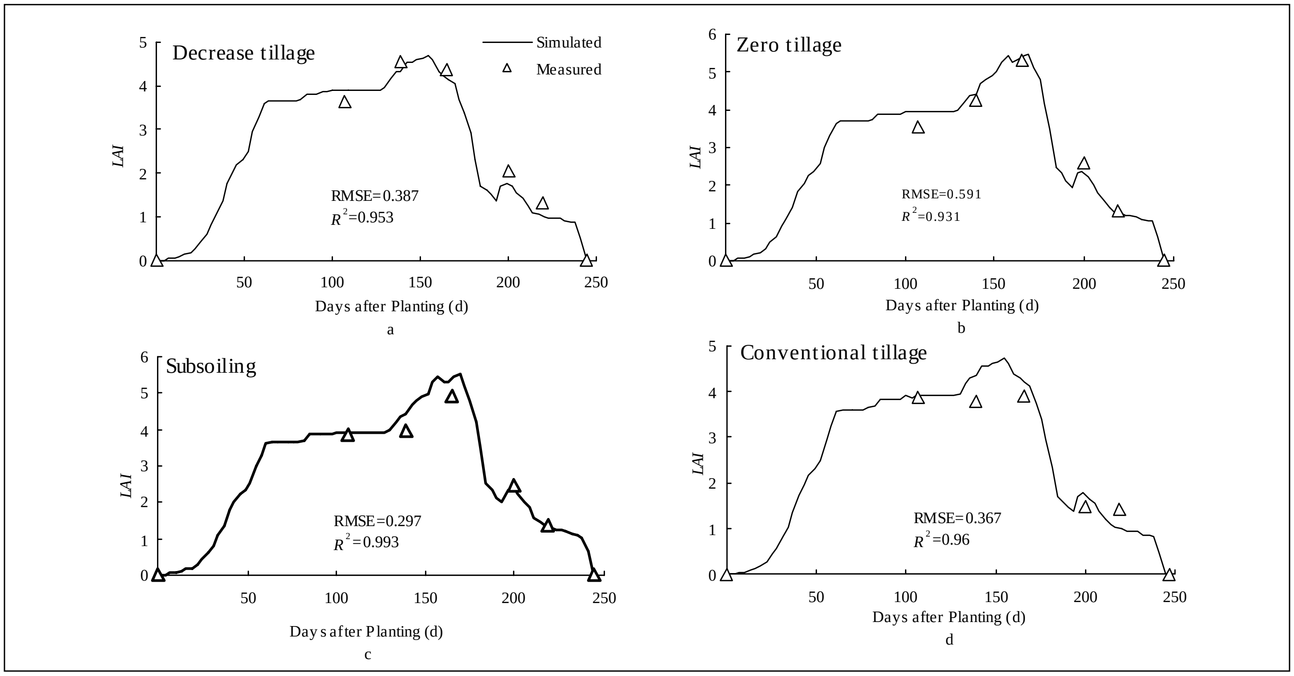

Figure 2. Comparison between simulated and measured Leaf Area Index for winter wheat during 2005-2006 growing season.

predicted and field observed values of the soil moisture. Measured soil moisture values were higher than simulated data (Figures 3 and 4), which may be because the measured data were impacted by field environments, such as site-specific precipitation and dew and the errors in storage of soil samples collected manually. Table 5 lists the RMSE of simulated and measured value of the soil moisture for four treatments. All the RMSE values were less than 0.151. The shape of the curve indicates that the current enhanced version of DSSAT is well suited for modelling soil water storage of winter wheat at the west Henan experimental site.

Water balance

The simulated water balance for the four treatments is presented in Table 6. The evaporative losses of DT and CT treatments were higher than ZT and SS treatments because the treatments of ZT and SS were covered with 35-40cm height wheat straw but DT and CT were covered only with 10-15cm height wheat straw. The wheat straw reduces evaporative losses effectively. Also, ZT and SS treatments significantly increased deep percolation compared with the DT and CT treatments.

The measured WUE values were derived from field measurements of wheat yield and water use (ET) at harvest, also, the simulated WUE values used simulated yield and ET. Table 7 shows that, similar to the measured data, the simulated grain WUE of SS is highest (16.58 $kg \cdot mm^{-1} \cdot ha^{-1}$) among the four tillage treatments. Table 7 shows that the error absolute values are less than 6.65%. The model predicted the WUE for all treatments reasonably well.

Table 5. RMSE of predicted soil moisture at various depths for the four treatments.

Treatment	Soil layer							
	0-5cm	5-15cm	15-30cm	30-45cm	45-60cm	60-90cm	90-120cm	120-150cm
	RMSE (cm^3?cm^{-3})							
DT	0.149	0.090	0.089	0.079	0.066	0.061	0.055	0.051
ZT	0.136	0.089	0.091	0.073	0.073	0.070	0.069	0.063
SS	0.142	0.093	0.092	0.085	0.078	0.070	0.067	0.081
CT	0.151	0.089	0.086	0.081	0.070	0.064	0.054	0.071

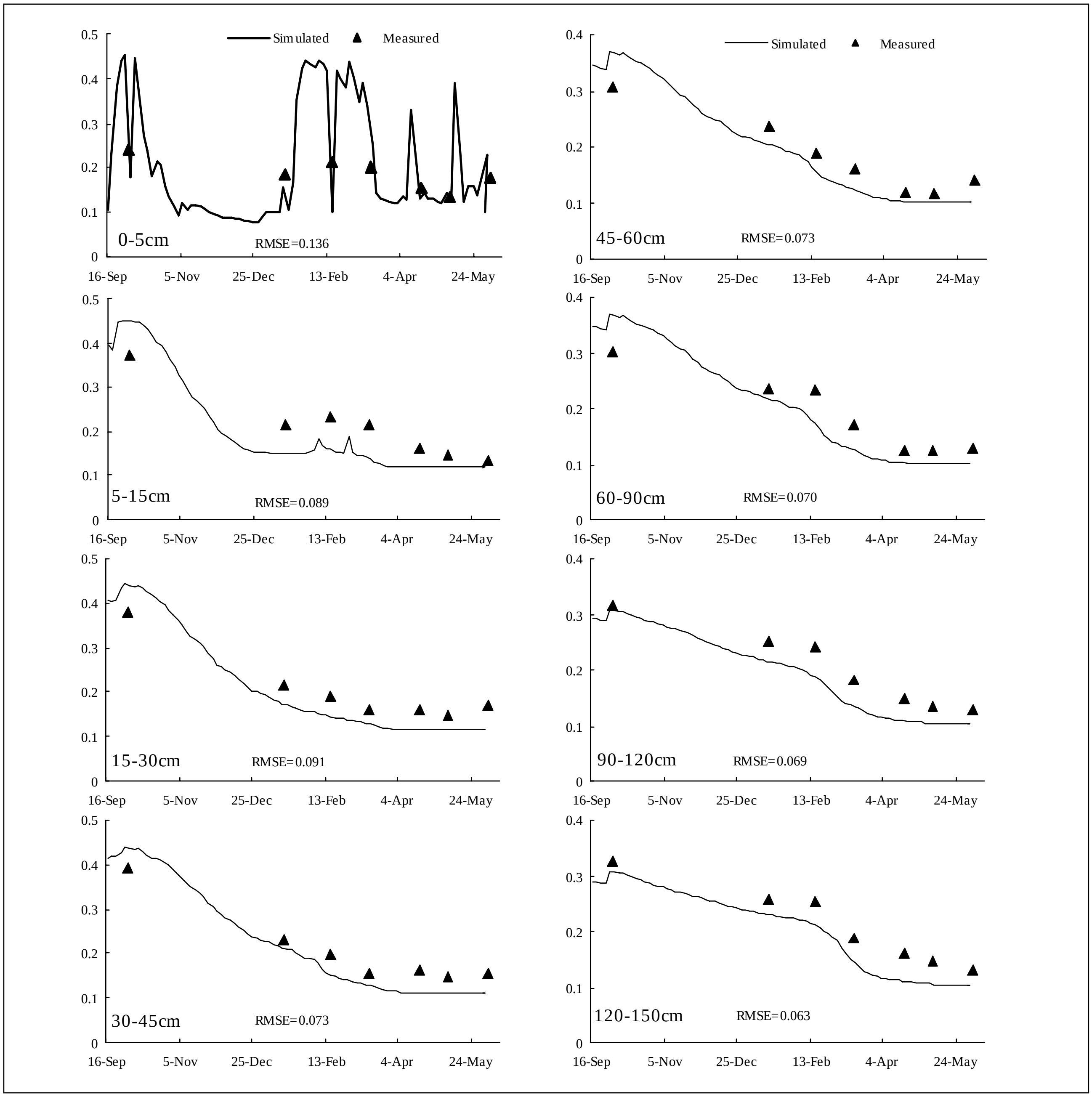

Figure 3. Comparison between simulated and measured soil moisture at various depths for the decrease tillage (DT) treatment.

Table 6. Measured simulated water balance in 150cm soil profile for four tillage treatments.

Treatments	T	E	D	ΔS
DT	177	67	27	-77
ZT	147	33	69	-55
SS	147	33	77	-63
CT	163	60	26	-55

Where T: transpiration, E: evaporation, D: drainage and ΔS: change in stored soil-water water use efficiency

SUMMARY AND CONCLUSIONS

The calibration results gave satisfactory agreement between field measured and model simulated values for crop yield with the difference between measured and simulated yield values being in the range of 0.58-3.94%. There was satisfactory agreement between measured and simulated LAI with

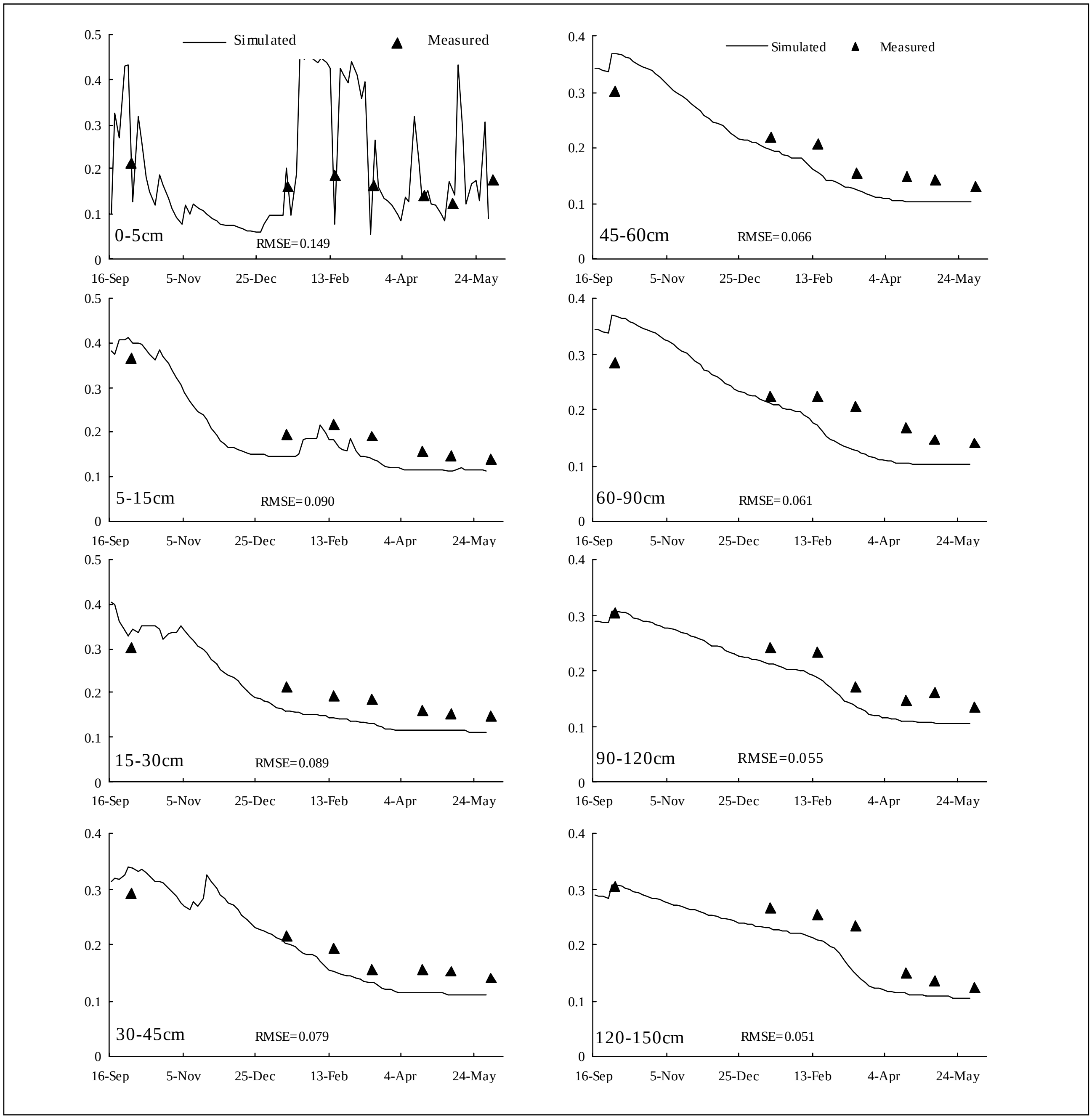

Figure 4. Comparison between simulated and measured soil moisture at various depths for the zero tillage (ZT) treatment.

Table 7. Comparison of measured and model simulated water use efficiency for four treatments.

Treatment	Measured	Simulated	Error
	----Kg·mm^{-1}·ha^{-1}----		%
DT	16.82	15.85	5.77
ZT	14.44	15.40	-6.65
SS	16.86	16.58	1.66
CT	15.66	15.81	-0.96

RMSE in the range of 0.297-0.591, and the regression coefficients r^2 ranged from 0.931 to 0.993. There was satisfactory agreement between measured and simulated soil moisture contents for the 150cm soil profile for all tillage treatments with RMSE ranging from 0.151 to 0.051.

The calibrated model was used for analyzing the changes in soil water balance for the four treatments and for computing the crop WUE. The simulated WUE for the four treatments was 15.85, 15.40, 16.58 and 15.81 $kg \cdot mm^{-1} \cdot ha^{-1}$, and 16.82, 14.44, 16.86 and 15.66 $kg \cdot mm^{-1} \cdot ha^{-1}$ was measured value of WUE for DT, ZT, SS and CT treatments, respectively. Analyses results showed satisfactory agreement between measured and simulated WUE for all tillage treatments with error ranging from 0.96% to 6.65%.

With this research we conclude that the enhanced version 4.5 of the DSSAT model can be applied to predict the LAI, yield and water balance of winter wheat in the west Henan region of China. These results are based on a four tillage treatment dataset over a one year period. Further analyses of predicted LAI and yield and water balance for long-term simulations of the treatments need to be carried out for improving the understanding of the conservation agriculture cropping system in the west Henan region of China.

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