Effects of Conservation Agriculture on Land and Water Productivity in Yellow River Basin, China

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Abstract: In the dryland regions of North China, water is the limiting factor for rainfed crop production. Conservation agriculture (featuring reduced or zero tillage, mulching, crop rotations and cover crops) has been proposed to improve soil and water conservation and enhance yields in these areas. Conservation agriculture systems typically result in increased crop water availability and agro-ecosystem productivity, and reduced soil erosion. To evaluate the potential of conservation agriculture to improve soil water balance and agricultural productivity, the DSSAT crop model was calibrated using the data of a field experiment in Shouyang County in the semi-arid northeastern part of the Yellow River Basin. The average annual precipitation at the site is 472 mm, 75% of which falls during the growing season. The site had a maize-fallow-maize rotation. data from two crop seasons (2005 and 2006) and four treatments for calibration and analysis were used. The treatments were: conventional tillage (CT), no-till with straw mulching (NTSM), all-straw incorporated (ASRT) and one-third residue left on the surface with no-till (RRT). The calibration results gave satisfactory agreement between field observed and model predicted values for crop yield for all treatments except RRT treatment, and for soil water content of different layers in the 150 cm soil profile for all treatments. The difference between observed and predicted values was in the range of 3%-25% for maize yield and RMSE was in the range of 0.03-0.06 cm^3/cm^3 for soil water content measured periodically each cropping season. While these results are encouraging, more rigorous calibration and independent model evaluation are warranted prior to making recommendations based on model simulations. Medium-term simulations (1995-2004) were conducted for three of the treatments using the calibrated model. The NTSM and ASRT treatments had similar or higher yields (by up to 36%), higher crop water productivity by up to 28% and reduced runoff of up to 93% or 43 mm compared to CT treatment.

Keywords: tillage, conservative agriculture, soil and water conservation, mulch, residues, CERES model, DSSAT model
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1 Introduction

In China, the easily eroded soil of the Loess Plateau dryland region is intensively cropped with dryland maize (*Zea mays* L.). Rainfed croplands comprise about 80% of the total cultivated land[1]. Rainfall distribution is

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uneven, with more than 60% concentration in the July-September period. Water is the most limiting factor for crop production. In this region, maize is planted in late April and harvested in mid-September. Because planting occurs right at the beginning of the rainy season, crop yields strongly depend on the amount of rain stored as soil moisture and this often mitigates the annual variation in precipitation. Traditionally, farmers leave their fields fallow during summer and practice conventional tillage (CT) to maximize soil water levels. But conventional farming with extensive cultivation and little use of crop residues exacerbates soil, water and nutrient losses, causing decreases in water availability, soil fertility and crop productivity. This has led to low crop yields and low land and water productivities. Conventional tillage in the dry farming areas of northern China involves moldboard plowing (animal drawn or motorized) to a depth of 16-18 cm, followed by a sequence of harrowing, smoothing, rolling and hoeing. These operations are done with all crop residues removed, being used as fodder for animals or as fuel[2]. Burning of crop residues has increased during the last few decades[3]. Intensive plowing has contributed to increasing risks of soil erosion by wind and water, and led to soil compaction and the formation of a hard pan in the subsoil layer[4]. It has also resulted in the depletion of soil organic matter, and reduction in soil structural stability, soil fertility and soil water retention[5].

Conservation agriculture (featuring reduced or zero tillage, mulching, crop rotations and cover crops) offers a possible solution. Conservation agriculture systems typically result in increased crop water availability and agro-ecosystem productivity, reduced soil erosion, increased soil organic matter and nutrient availability, reduced labor and fuel use, and increased biological control of pests. But the effectiveness of conservation agriculture on land and water productivity depends on soil type, crop water use requirements, rainfall distribution and amount, and soil-water storage capacity[6]. Some researchers found that switching from conventional tillage to conservation tillage improved soil-water storage capacity and crop yields[7-15], but Merril et al. [16], Tan et al.[17] and Mark and Mahdi[18] observed no difference among tillage systems in volumetric water content. Furthermore, Guzha[19] found that zero-till grain yields were lower than with CT, and Lampurianes et al.[20] found no difference among tillage systems in volumetric water content and water productivity. Baumhardts and Jones[21] compared conservation and conventional tillage and observed diverse results. Thus, before conservation tillage practices are widely adopted in any particular region, the suitability of this system should be assessed locally.

Several advances with conservation agriculture have been made in recent years in the northern provinces of China. Most of these studies have been in irrigated areas and have resulted in positive results[11,22,23]. The conservation practices generally involved a reduction in the number and intensity of tillage operations compared to conventional tillage, with direct sowing (“zero” or “no” till) as the largest reduction. Crop yields and water productivity have increased (by up to 35%) following the implementation of reduced tillage practices[24]. Under no-till, crop yields are equivalent to or higher than those from conventional tillage methods, especially in dry years. However, during wet years yields have tended to be lower (by 10%-15%) with no-till.

Crop growth simulation models can be useful in evaluating the impacts of different tillage systems on the changes in crop productivity and soil-water balance

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components. Compared to field experimentation, 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) [25], CropSyst (Cropping System Simulation Model)[26], DSSAT (Decision Support System for Agro-technology Transfer)[27], EPIC (Erosion Productivity Impact Calculator)[28], NTRM (Nitrogen-Tillage-Residue Management)[29] and PERFECT (Productivity Erosion and Runoff Functions to Evaluate Conservation Techniques) [30] have been developed and are being used to evaluate the impact of agricultural management practices. Simulation models offer a potentially valuable set of tools for examining questions related to the 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 development team has recently enhanced the model's capability by incorporating algorithms which can simulate the influence of conservation agriculture practices such as crop residue cover and tillage on soil surface properties and plant development. The modeling study reported in this paper is one of the first studies applying the enhanced DSSAT model for investigating the effects of conservation agriculture practices.

The objectives of this research were: 1) To calibrate the DSSAT crop simulation model for an experimental site in a dryland region of the Yellow River Basin; 2) To simulate, quantify and explain changes in yield and soil-water balance components with medium-term simulation of different conservation agriculture treatments.

2 Materials and methods

2.1 DSSAT model

DSSAT is a package which incorporates the CROPGRO and CERES crop growth models. The CERES-maize model is used to simulate maize cultivation. A detailed description of the CERES models can be found in Ritchie et al.[31]. The models predict the growth duration, average growth rates and the amount of assimilate partitioned to the economic yield components of the crop. They compute crop growth stages and morphological development using temperature, day length and cultivar characteristics. Biomass accumulation is based on the radiation use efficiency method, where the biomass is partitioned among the leaves, stems, roots, ears and grains. Biomass partitioning is based on the stage of development and general growing conditions. The partitioning is based on the source-sink concept and is modified when water and nutrient deficiencies occur. Crop yields are determined as the product of grain numbers per plant and average kernel weight at physiological maturity. The number of grains is calculated from the aboveground biomass accumulation during the critical growth stage for a fixed thermal time (or growing degree-days, which is computed based on the daily maximum and minimum temperatures) before anthesis. The grain weight in all CERES models is calculated as the product of cultivar-specific optimum growth rate and the duration of the grain filling. Grain fill is reduced below the optimum if there is insufficient supply of assimilates from daily biomass accumulation or stored mobile biomass in stems and leaves. When growth is source-limited, assimilates are redirected from the shoot to the roots.

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[32,33]. It follows a so-called "tipping bucket" approach incorporating rainfall, infiltration and runoff, drainage, soil evaporation, plant transpiration, root absorption or flow to an adjacent layer. The soil-plant-atmosphere module computes potential evapotranspiration (ET_0) according to the Priestley-Taylor or Penman-Monteith method (Doorenbos and Pruitt, 1977). The ET_0 is partitioned into potential soil evaporation and potential plant transpiration. Potential soil evaporation is estimated from the fraction of solar energy reaching the soil surface based on a negative exponential function of Leaf Area Index (LAI).

Actual soil evaporation is simulated in a two-stage process. After the soil surface is wetted by rainfall or irrigation, soil evaporation occurs at the potential rate until a certain amount after which the rate is reduced proportional to the square root of time elapsed. If evaporation is less than potential soil evaporation, the difference is added back to potential plant transpiration to account for the increased heat load on the canopy when the soil surface is dry.

In simulations, the modified Priestly-Taylor method is used to estimate evapotranspiration. We used DSSAT version 4.5 which includes the new tillage model based on the improved CERES-Till[34] - 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.[35] improved the CERES-Till model which now accounts for residue incorporation and its effects on the soil nutrient balance as well as the water balance and soil temperature. The model has provisions for the input of tillage date, type of 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.[35].

2.2 Site description

The experimental site is located in Zong Ai village, Shouyang County (37º32'-38º6' North latitude, 112º46'-113º54' East longitude) (Figure 1) which belongs to the warm-temperate zone and semi-arid grassland region in the sub region of Shaanxi-Gansu-Ningxia gully region of loess plateau. Table 1 describes some of the characteristics for the experiment site.

The annual precipitation in Shouyang is generally low and is distributed non-uniformly in space and time, and often as large rainstorms (Figure 2). Droughts are very common with frequency in the range of 60% to 80%. Drought frequency during the spring to summer period ranges from 53% to 77%. The longest drought period was 140 d in 1973.

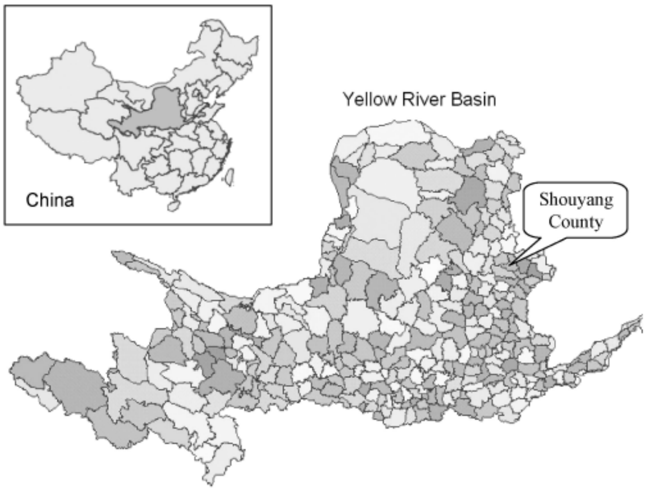


Figure 1 Location of the experimental site in the Yellow River Basin

Table 1 Site characteristics

Characteristic	Value
Elevation above mean sea level	1,135 m
Annual ≥10℃ accumulated temperature	2,500-3,100℃
Annual average temperature	7.6℃
Lowest temperature ever recorded	-26.6℃
Highest temperature ever recorded	35.5℃
Annual precipitation	350-550 mm (average: 491.3 mm)
Potential Evapotranspiration (PET)	852 mm
Average frost-free period	135-168 d
Average total annual sunlight	2,518 h
Average total radiation	535.9104 kJ/cm^2

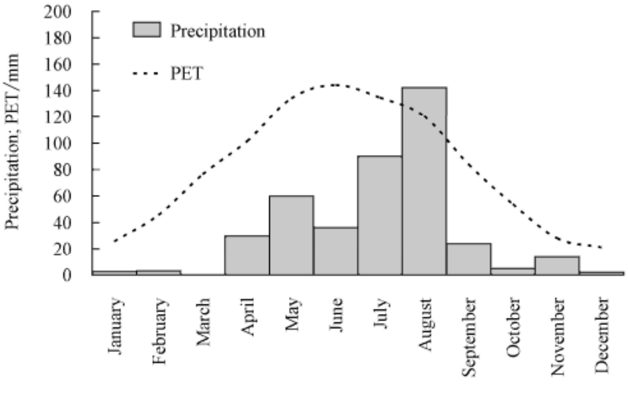


Figure 2 Average (50-year) precipitation and potential evapotranspiration (PET) at the experiment site

Since precipitation is low and much less than PET, there is not enough soil moisture to grow more than one crop per year. Monoculture is a common practice in the region. A maize-fallow-maize annual cropping experiment comparing conventional tillage and conservation agriculture practices has been conducted at Zong Ai since 2005[36], and the data from 2005 and 2006 were used to calibrate and evaluate the DSSAT model.

2.3 Experimental design and monitoring

Maize (cv Jindan34) was grown from April-September each year. There were three conservation agriculture treatments and one conventional tillage treatment on four adjacent fields[36]. Each treatment was replicated three times. Crops were planted on April 29 of each year at 60,030 plants/ha, 10-15 cm depth, and row spacing of 0.6 m. Ammonium polyphosphate was applied at planting alongside the seed at a rate of 600 kg/ha (N-P_2O_5-K: 20-60-0) on April 29 of each year. Each plot was 667 m^2 in size. There was a seven-month fallow period between harvest of the maize in autumn (October) and planting in spring (May) in the following year.

Table 2 describes the four treatments carried out at the experiment site. For the conventional tillage (CT) treatment, most residues of the previous maize crop were removed for fodder, leaving 10-15 cm stubble on the field after harvest (in October), after which the field was plowed by a tractor drawn plough to 20-25 cm depth, turning the soil over. During spring (in April), the field was harrowed (to 5-8 cm depth) by tractor drawn harrows, just before sowing. A human-drawn chisel planter was used for sowing. At the same time, fertilization was done by hand. For the ASRT treatment, all residues of the previous maize crop (3 t/ha) were plowed into top 20-25 cm soil layer by tractor. In spring, the field was harrowed (to 5-8 cm depth) by tractor drawn harrows. A human-drawn chisel planter was used for sowing. At the same time, fertilization was done by hand. In the NTSM treatment all residues of the previous maize crop were flattened and mulched in the field. Direct seeding and fertilization were performed by hand in the spring. For RRT treatment all maize residues were removed after harvest, and about one-third of maize residues were chopped and incorporated into the top 15 cm soil layer in autumn using a rotary plow. Direct seeding and fertilization were performed in spring using the no till planter.

Table 2 Description of conservation agriculture treatments at the experiment site[36]

Treatment	Planting date	Fertilizer application /kg · ha^{-1}	Tillage operations and residue management
Conventional Tillage (CT)	April 29	600	All maize straw was removed after harvesting; during spring, plowing and harrowing operation were carried out prior to sowing
No-Till with Straw Mulching (NTSM)	April 29	600	All maize straw was chopped and mulched in the field; in spring, direct seeding and fertilizer application were simultaneously applied using the no-till drill
All Straw with Return Till (ASRT)	April 29	600	All the previous maize straw was returned to field and plowed into top 20cm soil layer. The following year, sowing and fertilizer application were carried out simultaneously using a human-drawn chisel planter
One-third residue left with rolling till (RRT)	April 29	600	One-third of maize straw was left standing in the field; in spring, the straw was chopped and seed and fertilizer sown in a single pass

Gravimetric soil water content was measured on samples collected (using soil drill) from different depths up to 200 cm, at three locations within each plot. Measurements were made at 10-14 day intervals from May 2005 to October 2006. Soil moisture was determined by calculating difference between weight of soil samples before and after drying in an oven at 105℃ for 24 h. Soil organic matter was determined by wet oxidation[37] and the percentage of organic carbon was calculated by applying the Van Bemmelen factor of 1.73. Soil samples were collected from the 0-10 cm soil layer (3 replicates for each treatment, bulked by soil layer). Soil bulk density was measured at 0-15, 15-30, 30-60, 60-80 and 80-100 cm depths at three locations within each treatment. The soil bulk density was measured in April 2005 a few days before planting. For the 100-150 cm depth, soil bulk density was derived using the SBuild pedotransfer function in-built into DSSAT[38]. Table 3 presents the soil bulk density and particle size distribution. The particle size distribution (clay, silt and sand content) and hydraulic conductivity were acquired from the Shouyang County Soil Survey Handbook.

Maize grain yield was determined by harvesting an area of 4 m^2 in each plot at maturity. The maize grains were dried in an oven at 80℃ for 24 hours. Maize maturity date was based on the advice of the research staff in-charge of the experiment site. The date was chosen when the bract of the ears completely became pale, a black layer formed on the grain and the kernel moisture content reached about 33%.

Table 3 Soil physical properties and initial conditions used for the DSSAT simulations.

Soil depth /cm	Saturated hydraulic conductivity#/cm • h^{-1}	Organic Carbon /mg • kg^{-1}	Bulk density /g • cm^{-3}	Sand#/%	Silt#/%	Clay#/%	Drained upper limit* /mm • mm^{-1}	Drained lower limit* /mm • mm^{-1}
0-15	0.68	8.7	1.37	20.7	55.1	24.2	0.28	0.14
15-30	0.68	6.9	1.32	16.7	57.1	26.2	0.30	0.15
30-60	0.68	4.4	1.30	12.6	67.1	20.3	0.29	0.12
60-80	0.68	5.7	1.30	16.7	57.1	26.2	0.30	0.14
80-90	0.68	3.3	1.30	17.0	58.9	24.1	0.27	0.13
90-150	1.32	4.3	1.29*	28.9	49.0	22.1	0.21	0.11

Note: # from the Shouyang County Soil Survey Handbook; * Derived using SBuild pedotransfer function[38].

Weather data (including maximum and minimum ambient air temperature, precipitation and solar radiation) were downloaded for the county weather station from the Chinese national weather service website. The weather station is located approx. 20 m from the experimental plots. The 2006 precipitation was measured using an automated weather station installed at the experimental site using a tipping-bucket automatic rain gauge. Table 4 presents monthly total precipitation for the simulation period. Precipitation varied greatly between the two years, especially during April, June and August; 2005 was a relatively dry year and 2006 was a normal precipitation year. During the growing season, the 2005 precipitation was 39% lower and 2006 precipitation was 6% lower than the long-term average of 413 mm. The 2005 and 2006 fallow period rainfall was 35% and 39% less than the long-term average fallow rainfall (58.7 mm), respectively.

Table 4 Monthly total precipitation received at the experiment site from January 2005 to December 2006, and the long term average, at the experimental site

mm

	Month	2005	2006	Average
Maize cropping season	January	0.2	3.5	2.8
	February	5.2	7.9	3.8
	March	2.5	0.0	16.4
	April	6.6	25.6	18.2
	May	37.1	38.7	47.0
	June	30.8	84.8	68.9
	July	42.9	39.1	105.0
	August	77.6	155.5	120.0
	September	68.4	45.5	54.0
	October	3.0	8.8	23.0
	November	0.0	13.4	11.6
	December	0.4	2.0	1.1
	Total cropping season	263.4	389.2	413.1
	Total yearly	274.7	424.8	471.8

2.4 Model parameterization and calibration

The DSSAT model was run in its “sequence analysis” mode for this study. In “sequence analysis” mode, the soil parameters at the end of a simulation year were carried over to the first day of the following simulation year. In this way there is a continuation of simulation unlike the “experiment mode” in which the model is reinitialized on the first day of the following simulation year. The model was calibrated by adopting the procedure laid out by Hu et al.[39] using site-specific soil hydraulic properties and plant growth parameters for the site and the crop being simulated. Field measured values of weather parameters, crop management and soil properties were used for setting up the DSSAT model. Missing data such as soil drained upper limit, the lower limit and saturation soil water content were estimated using the soil data tool-SBuild pedotransfer function[38] in DSSAT. The initial C:N ratio was set to 11 (default DSSAT value) and soil mineral nitrogen to 0.022%. We used the iterative approach of Godwin et al.[40] to reach reasonable estimates of the genetic coefficients of the DSSAT crop models through trial-and-error adjustments to match the observed phenology and yield with simulated values. A literature review was carried out and values for an irrigated maize cultivar grown in north China[41] were used as the baseline values. We modified the coefficients one at a time to check sensitivity of output to their change. We searched for optimum values of coefficients in increments of 5% between specific lower and upper bounds, based on literature and default values available.

We calibrated the model for maturity date, grain yield at harvest and soil moisture content of different layers for all treatments during the growing season. The accuracy of the model predictions was determined by computing the percentage error in crop yield prediction and the root mean square error (*RMSE*) in predicting daily soil moisture. The *RMSE* is defined as:

$$RMSE=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(p_i-o_i)^2} \tag{1}$$

Where: n is the number of values; p_i and o_i are the predicted and observed values, respectively.

2.5 Model simulations

Using the calibrated model, we simulated the medium-term (1995-2004) effects of the conservation agriculture and conventional tillage treatments on land and water productivity and components of the water balance. The field-scale soil water balance can be written as:

$$\Delta S=P-E-T-D-R \tag{2}$$

Where: ΔS is the change in soil-water storage; P is precipitation; E is soil evaporation; T is crop transpiration, D is deep percolation and R is surface runoff. In this study, deep percolation was set to zero following advice of fellow regional researchers. Crop water productivity (WP) was defined as:

$$WP=\frac{Y}{ET} \tag{3}$$

Where: WP represents water productivity for crop, kg/m^3; Y is grain yield of maize, kg/ha; and ET is the evapotranspiration during the year, mm.

3 Results and discussion

3.1 Model Calibration

Calibrated genetic coefficients for plant growth are listed in Table 5.

Table 5 Calibrated genetic plant growth coefficients in DSSAT for simulation of maize (cv. Jindan34) at the Shouyang experiment site

Parameter	Value
Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8°C) during which the plant is not responsive to changes in photoperiod	250.0
Extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 h)	0.7
Thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8℃)	950.0
Maximum possible number of kernels per plant	510.0
Kernel filling rate during the linear grain filling stage and under optimum conditions (mg/d)	11.0
Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances	75.0

In addition to the genetic plant growth coefficients, we modified some soil-water parameters to match the field observed soil moisture data with the model predicted data. We changed the runoff curve number from model default value of 81 to 73, soil albedo from the model default value of 0.13 to 0.10, soil fertility factor from the model default 1.0 to 0.8, soil slope from 0 to 2%, and soil drainage rate from 0.4 to 0.5. By changing these parameters, we found a better match for soil moisture and grain yield; and predicted PET (900 mm/y) was also very close to the 852 mm/y reported for Shanxi Province in Wang et al.[24]. The combination of cultivar and soil-water parameters that gave the minimum error for yield, daily soil moisture and maturity date was selected.

3.2 Model evaluation

3.2.1 Crop yield

Grain yield at harvest for all four treatments during the two cropping seasons of the experimental period, 2005-2006, was used for model calibration. Table 6 lists the values and their respective prediction differences. There was generally good agreement between predicted and observed yield, except for RRT in 2006. There was a high error (25.2%) in predicting yield for RRT during 2006 season which we cannot explain.

Less rainfall in 2005 compared to 2006 resulted in lower grain yield of CT in 2005, which was also predicted by the model. During the dry year (2005), the model predicted the highest yield with NTSM, but during the normal year (2006) the predicted yield of NTSM was much lower than yield of all other treatments, consistent with the observations by Cai and Wang[4]. They reported that, spring maize seedling emergence with conservation tillage (subsoiling between rows or no-till with whole maize stalk mulching after fall harvest, and direct seeding the following spring) was 2-3 days earlier and 17%-23% higher in a dry spring in Shouyang County, but that the benefit of conservation tillage was much less in a relatively wet year. Similar results have been reported for Shouyang County by Cai and Wang[4] where surface temperature under mulch during crop establishment decreased by 2-6℃ compared with stubble removed or incorporated, thus affecting establishment and crop yield. While the differences between observed and predicted yields of the conventional and conservation agriculture treatments are generally small, the results show that the model is sensitive to the differences between treatments.

Table 6 Comparison of observed (standard deviation of observed yield) and model predicted crop yield results during the calibration period

Year treatment	Observed$^{\%}$ (SD) $/10^{3}$ kg · ha^{-1}	Simulated $/10^{3}$ kg · ha^{-1}	Error* /%
2005	Grain yield		
CT	4.73^{b} (0.12)	5.29	12.0
NTSM	5.18^{a} (0.27)	5.74	10.2
ASRT	5.30^{a} (0.33)	5.13	-3.1
RRT	4.65^{b} (0.07)	5.05	8.7
2006	Grain yield		
CT	6.14^{a} (0.27)	6.34	3.3
NTSM	4.62^{c} (0.28)	4.48	-2.3
ASRT	5.58^{b} (0.31)	5.74	2.8
RRT	4.91^{c} (0.23)	6.14	25.2

Note: CT: conventional tillage treatment, NTSM: no-till with straw mulching, ASRT: all straw with return till treatment, RRT: One-third residue left with rolling till. % Values marked with the same letter are not significantly different at p=0.05 within each year. *Negative sign represents under-prediction

3.2.2 Soil water content

Soil layers of thickness 5-15, 15-30 and 30-45 cm are important for simulating correct plant water uptake and thus the soil-water balance. Soil moisture dynamics in the surface soil layers (0-5 cm) are more complex than deeper layers due to high spatial and temporal variations in organic matter content, macroporosity, and other properties. Figure 3 shows very good agreement in soil water content of simulated and observed values throughout the profile to 45 cm in the conventional tillage treatment. There was similar agreement between the model predicted and field observed values of the daily soil moisture for all treatments (data not presented) with the RMSE ranging from 0.03 to 0.06 cm^{3}/cm^{3}. Furthermore, simulated as well as observed soil water content was higher at depth under all three conservation agriculture treatments than under conventional practice[36], resulting in up to 15% more deep percolation for ASRT treatment in 2006 (normal rainfall year). Soil moisture for all treatments was relatively constant from seeding to seedling emergence. At this stage the crop water requirement is limited and the differences in soil moisture mainly stem from treatment effects. In general, the soil moisture strongly depends on the rainfall.

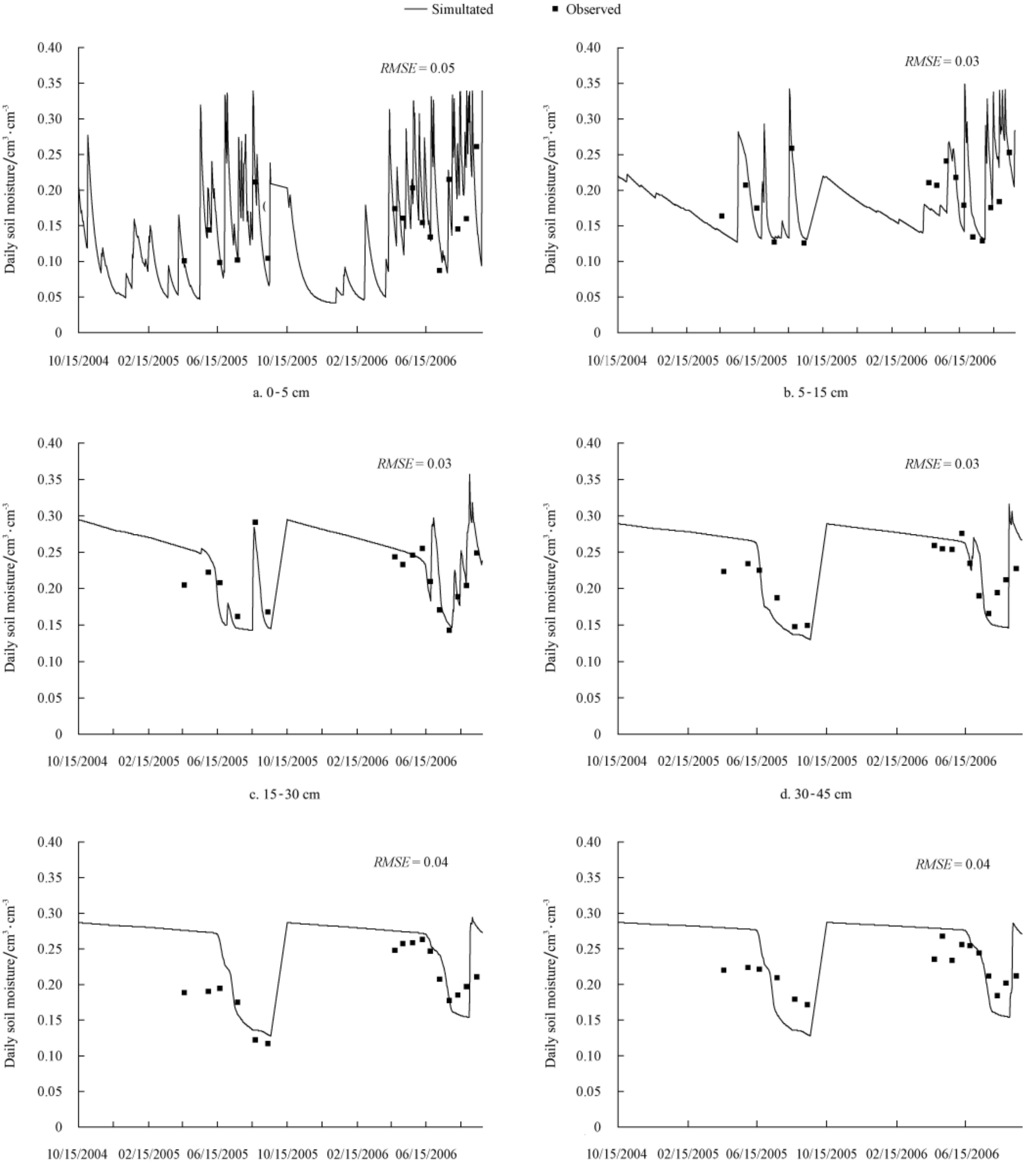
Once there was satisfactory agreement between observed and model predicted values for crop yield and daily soil moisture content, we applied the model for predicting medium-term changes in land and water productivity with the adoption of conservation agriculture practices at the site.

3.3 Medium-term simulations

Simulations were conducted for 1995-2004 to predict the medium-term field-scale changes in yield, soil-water balance components and water productivity for NTSM and ASRT in comparison with CT. As there was a very high prediction error during calibration of the model for RRT (Table 6), did not include that treatment in the medium-term analyses.

3.3.1 Crop Yield

Predicted yields varied with seasonal conditions; for example, yield of CT varied from about 4,500 kg/ha in 1997 to about 7,500 kg/ha in 2002 (Figure 4). The NTSM and ASRT conservation agriculture treatments always had similar or higher crop yields compared to CT. During the first three years of simulation (1995-1997), the differences in crop yields between treatments were small but were much larger after that. In maize-wheat systems in Mexico, Sayre et al.[15] also found that the benefits of conservation agriculture treatments only became apparent after several years. The reasons for the relatively small differences between yields of CT and NTSM and ASRT during later years 2003 and 2004 are not known. Growing period rainfall of 2001 (235.5 mm) was very low compared to long-term average rainfall of 413 mm. In that year NTSM and ASRT generated about 36% higher crop yields than CT. The yield trends were affected by pre-season (fallow) rainfall which was better conserved in NTSM and ASRT than CT. During normal rainfall cropping periods also the crop yields for NTSM and ASRT treatments were higher by 5%-27%. In maize-wheat systems in Mexico, Govaerts et al.[42] also showed the importance of residue retention on the soil surface in no till systems, where yields declined in the absence of residue retention after the first few years[42].



a. 0-5 cm

b. 5-15 cm

c. 15-30 cm

d. 30-45 cm

e. 45-60 cm

f. 60-120 cm

Figure 3 Comparison between predicted and observed soil moisture (n=16 at each depth) at various depths for the conventional tillage (CT) treatment at the Shouyang experiment site. Units of root mean squared errors (*RMSE*) of soil moisture predictions are cm^3/cm^3

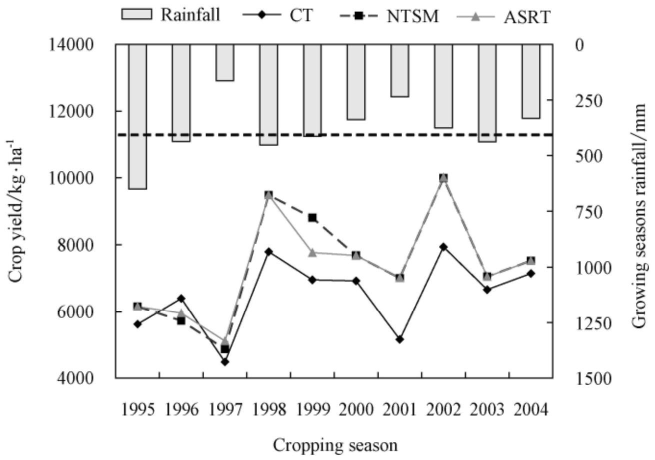


Figure 4 Comparison of predicted crop yields for conventional tillage (CT), no till straw mulching (NTSM) and all straw return till (ASRT) during the 1995-2004 simulation period. The broken line shows the long-term average growing season rainfall (413 mm)

3.3.2 Soil water balance

The soil-water balance comprises gains and losses in the soil-water storage (ΔS). In dry areas such as Shouyang County transpiration is a beneficial loss, while run-off and deep drainage are losses to the cropping system (but may have downstream and ecosystem benefits). Soil evaporation in such places is a non-beneficial loss. The predicted soil-water balance was compared for CT, NTSM and ASRT over the crop and fallow periods. The fallow period is generally used for recharging the soil moisture[43]. But at this site the rainfall magnitude and distribution is such that except for the 1995 cropping period, and the 1997 and 1999 fallow periods, there was a net loss of soil water in all crops and fallow periods (Table 7). This is consistent with the fact that there is a 60% to 80% probability of drought in the Shanxi Province to which this site belongs. These results are also in line with Wang et al. [24] who report a water deficit of 414-493 mm/y for Shanxi Province.

Table 7 Components of the water balance for the four treatments

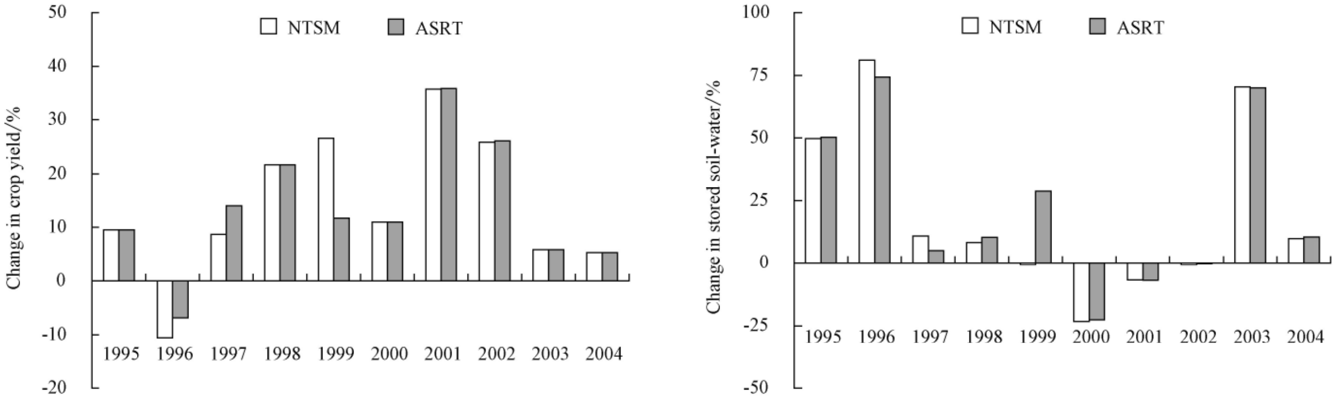
	Fallow Period					Cropping Period						Yield /10^3 kg·ha^{-1}	WP /kg·m^{-3}
	P/mm	E/mm	R/mm	D/mm	ΔS/mm	P/mm	T/mm	E/mm	R/mm	D/mm	ΔS/mm		
1995						29 April, 1995-6 November, 1995							
CT						650	235	196	144	0	75	5.62	1.30
NTSM						650	246	190	101	0	112	6.16	1.41
ASRT						650	246	190	101	0	113	6.16	1.41
1996	7 November, 1995-28 April 1996					29 April, 1996-4 November, 1996							
CT	64	73	0	0	-9	436	235	184	56	0	-39	6.40	1.30
NTSM	64	72	0	0	-9	436	216	187	34	0	-1	5.72	1.20
ASRT	64	72	0	0	-7	436	219	187	34	0	-4	5.96	1.25
1997	5 November, 1996-28 April 1997					29 April 1997-18 October, 1997							
CT	109	95	5	0	10	164	211	107	7	0	-161	4.43	1.08
NTSM	109	94	2	0	12	164	199	110	2	0	-148	4.87	1.21
ASRT	109	94	2	0	13	164	208	110	2	0	-157	5.11	1.24
2000	29 October, 1999-28 April, 2000					29 April 2000-30 September, 2000							
CT	31	71	0	0	-40	337	238	126	24	0	-51	6.92	1.59
NTSM	31	71	0	0	-40	337	268	117	24	0	-72	7.68	1.68
ASRT	31	70	0	0	-39	337	268	117	24	0	-72	7.68	1.68
2001	1 October, 2000-28 April, 2001					29 April, 2001-26 September, 2001							
CT	10	86	0	0	-76	236	221	104	27	0	-116	5.16	1.25
NTSM	10	86	0	0	-75	236	256	97	13	0	-130	7.01	1.59
ASRT	10	85	0	0	-75	236	256	97	14	0	-131	7.01	1.60
2002	27 September, 2001-28 April, 2002					29 April, 2002-19 October, 2002							
CT	11	86	0	0	-76	375	290	151	40	0	-105	7.94	1.55
NTSM	11	86	0	0	-75	375	310	148	23	0	-106	9.99	1.89
ASRT	11	85	0	0	-75	375	311	148	23	0	-106	10.01	1.89
2003	20 October, 2002-28 April, 2003					29 April, 2003-19 October, 2003							
CT	92	119	1	0	-28	437	244	151	36	0	6	6.66	1.29
NTSM	92	119	0	0	-27	437	252	147	18	0	20	7.05	1.36
ASRT	92	119	0	0	-27	437	252	147	18	0	21	7.05	1.36

	Fallow Period					Cropping Period						Yield $/10^3$ kg·ha^{-1}	WP /kg·m^{-3}
	P/mm	E/mm	R/mm	D/mm	ΔS/mm	P/mm	T/mm	E/mm	R/mm	D/mm	ΔS/mm		
2004	20 October, 2003-28 April, 2004					29 April, 2004-15 October, 2004							
CT	51	87	1	0	-37	331	253	140	24	0	-86	7.15	1.49
NTSM	51	86	0	0	-35	331	253	141	13	0	-75	7.53	1.57
ASRT	51	86	0	0	-35	331	252	141	13	0	-75	7.53	1.57

Note: * Negative sign represents net loss of soil-moisture at the end of the period.

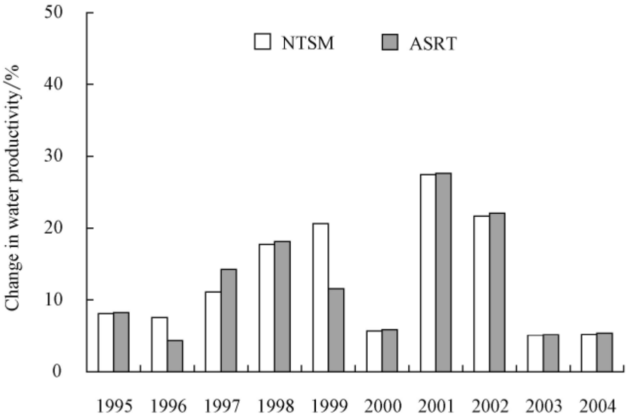
Figure 5 shows the relative change in crop yield, soil water and water productivity with respect to *ET* for the three treatments. The two conservation agriculture treatments performed better than CT in terms of grain yield and water productivity. During 9 out of 10 years, grain yield of NTSM and ASRT was higher than of CT. During 6 out of 10 cropping periods and all 9 fallow periods the evaporation losses of NTSM and ASRT were lower than of CT, however the differences were very small, greatest values being about 10 mm (Table 7). This probably reflects the generally dry conditions in this region, and thus the limited scope for mulch to reduce evaporation. The largest benefits of the conservation agriculture treatments were reduced runoff, by up to 43 mm during the cropping season .

Soil erosion caused by surface runoff is a major problem in the Yellow River Basin. This is degrading water quality in the Yellow River. The conservation agriculture treatments reduced runoff and thus may help reduce erosion (Table 7).



a. Crop yield

b. Stored soil-water



c. Water productivity (with respect to ET)

Figure 5 Predicted changes in crop yield, stored soil-water, and water productivity (with respect to ET) for the three conservation agriculture treatments relative to the CT treatment during the 1995-2004 simulation period

4 Conclusions

To evaluate potential to improve land and water productivity with adoption of conservation agriculture practices, the DSSAT crop model was calibrated and applied to the Shouyang County experiment site in the Shanxi Province of the Yellow River basin of China. The calibration results gave satisfactory agreement between field observed and model predicted values for crop yield with differences between observed and predicted values normally in the range of 2.8%-12%. There was good agreement between observed and predicted daily soil moisture contents for all treatments with RMSE in the range of 0.03-0.06 cm^3/cm^3. While these results are encouraging, more rigorous calibration and independent model evaluation are warranted prior to making recommendations based on model simulations.

The calibrated model was used for analyzing the medium-term changes in crop yield, soil-water balance and crop water productivity for CT, NTSM and ASRT. The conservation agriculture practices increased grain yield by up to 36%, soil-water storage by up to 81%, and water productivity by up to 28%, while runoff was reduced by up to 93% or 43 mm. The reductions in soil evaporation with the conservation agriculture treatments were always very small during both the fallow period and cropping season.

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