

# Conservation Tillage Impacts and Adaptations in Irrigated Corn Production in a Humid Climate

Saseendran S. Anapalli,\* Krishna N. Reddy, and Sindhu Jagadamma

## ABSTRACT

We initiated a long-term experiment in 2008 on 1.25-ha farm-scale plots to assess the production impacts of no-till with full residue retention (NT) system over a conventional tillage (CT) system under irrigated corn (*Zea mays* L.) production on a Dundee silt loam soil in a humid climate. Data collected in the experiment from 2009 to 2015 were mainly confined to grain yield at harvest. In 2016 and 2017, additional data were collected including soil surface crop residue mass and soil surface residue cover; corn leaf area index (LAI) and biomass; soil water, temperature, N, C, and bulk density ( $D_b$ ); and the corn phenology. In 7 out of 9 yr (2009–17), harvested grain yields under NT were significantly lower than those harvested under CT. To investigate the possible reasons for the yield decreases under NT, we integrated the experiment with the Root Zone Water Quality Model to synthesize information on the various components in the system. The N loss to runoff and deep percolation, denitrification caused by higher soil water content, and a low N mineralization rate caused by lower soil temperatures under NT potentially contributed to the observed grain yield decrease under this treatment. Simulations showed that an additional N application at 40 kg ha<sup>-1</sup> at planting or a split application of 50 kg ha<sup>-1</sup> at planting and the remaining 174 kg ha<sup>-1</sup> in the second week of May could make the yield return under NT comparable to that under CT.

## Core Ideas

- No-till land management (NT) decreases corn production in a humid climate.
- The reasons for reduced yield were investigated by integrating system models with experiments.
- Soil N deficiencies under NT possibly contributed to the yield decrease.
- Split application or enhancing N rate can compensate for the yield decrease under NT.

CONVENTIONAL TILLAGE increases soil erosion potential and associated losses of C and N to natural events like wind and rain (Gilley and Doran, 1997; Busari et al., 2015). It can also affect the soil's physical properties (e.g., water holding capacity and hydraulic conductivity), thus changing the soil water availability for plant uptake and its loss to evapotranspiration. Intensive tillage can also accelerate greenhouse gas emissions from the soil and deteriorate water quality (Mangalassery et al., 2014; Lal et al., 2007; Lal and Shukla, 2004; Anikwe and Ubochi, 2007; Allmaras et al., 1977). Adoption of conservation agriculture (CA) land management practices that have the potential to achieve optimum crop yields with minimum damage to the environment was recommended to ameliorate the adverse impacts of CT on the soil–water–air environment. At the heart of the CA principle is NT, a system of tillage operations designed to leave 30 to 100% of the soil surface covered with past crop residues. These crop residues on the soil surface help to reduce wind and water erosion of the soil resources (Busari et al., 2015). Numerous studies have reported the benefits of CA over CT. At one end of the spectrum of CA is the NT system in which seeds for the next crop are normally drilled into the soil with the residue cover. The NT system has been viewed as the CA practice that is capable of producing the maximum benefits from both no soil disturbance and increased soil cover. In NT, in addition to the savings on cultivation costs, various other advantages related to soil and water conservation and environmental quality have been reported: better soil physical and chemical properties (Benjamin, 1993; Lal, 1997; Anikwe and Ubochi, 2007); better soil nutrients (Ismail et al., 1994; Rahman et al., 2008), better root growth resulting from cracks, wormholes, and biopores (Francis and Knight, 1993), better C sequestration in the soil (Alvarez, 2005; Lal et al., 2007), and reduced emissions of greenhouse gases (e.g., CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O) (Steinbach and Alvarez, 2006; Kessavalou et al., 1998).

With an area over four million ha, the Mississippi Delta is one of the largest contiguous crop production areas in the United States (Snipes et al., 2005). The lower Mississippi Delta region receives about 70% of its annual rainfall (130 cm yr<sup>-1</sup> on average based on 1960–2015 data) during the winter and spring months (September–April) (Anapalli et al., 2016b). However, the

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**Abbreviations:** CA, Conservation agriculture; CT, conventional tillage;  $D_b$ , bulk density; LAI, leaf area index; MD, mean deviation; NT, no-tillage; RMSD, root mean squared deviation; RZWQM2, Root Zone Water Quality Model.

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principal crops in the area [soybean (*Glycine max* [L.] Merr., cotton (*Gossypium hirsutum* L.), corn, and rice (*Oryza sativa* L.)] are grown during the summer (April–September) months for meeting the optimum temperature demands of these crops. The high clay content of the soils, combined with heavy rainfall received in this region, often limit tillage operations for seedbed preparations at planting in the spring. Tillage operations, therefore, are usually performed after harvest of the previous crop (i.e., during October and November) (Snipes et al., 2005). This practice makes the tilled soil vulnerable to C and fertility losses to water and wind erosion during the fallow months. Tillage also modifies rainwater infiltration, runoff, and deep percolation processes, culminating in poor rainwater use efficiency in the cropping systems in the region. The NT practice can potentially ameliorate these problems related to tilling the soil and add organic matter to improve soil qualities and the availability of nutrients for crop growth. However, the location-specific viability of the NT system, especially in producing sustainable crop yields, depend on the growing season climate and soil properties (Wang et al., 2006; Pittelkow et al., 2015; Stevenson et al., 2014; Giller et al., 2011). On the basis of a global meta-analysis of 610 field trials that compared NT with CT across 48 crops and 63 countries, Pittelkow et al. (2015) reported significant grain yield decreases under NT systems. Notwithstanding, they also pointed out that the NT system, especially with residue retention, can retain grain yield returns on par with the CT systems in certain dry climates. Identification of the possible reasons for yield decreases in specific soils and climates and developing soil–water–crop management alternatives for combating those problems can lead to better acceptance of NT for its benefits to the environment.

Agricultural systems exhibit complex interactions of biological, physical, and chemical processes in the crop–soil–water interface. As such, collecting data representing all these processes and their interactions is unfeasible. However, integrating the data collected from field experiments into agricultural system simulation models and simulating these processes and their interactions can help in exploring soil–water–nutrient management changes for adaptation of NT across climates and soils (Ahuja et al., 2000; Jones et al., 2003; Saseendran et al., 2008). In this context, the RZWQM2 (Root Zone Water Quality Model) is a process-oriented agricultural system model that is capable of simulating the effects of tillage, crop residue, water, fertilizer, manure, and crop management on crop production and water quality (Ahuja et al., 2000; Saseendran et al., 2013; Ma et al., 2009). It contains the CSM-CERES-Maize version 4.6 (currently updated to this version) model for simulation of corn (Ma et al., 2005, 2006, 2009; Jones et al., 2003). In RZWQM2, the Green–Ampt equation simulates infiltration of rain and irrigation water, and then the water that enters the soil is redistributed between different soil layers by the Richards' equation (Ahuja et al., 2000). The Shuttleworth–Wallace equation, modified to include the surface crop residue dynamics on aerodynamics and energy fluxes, computes potential evapotranspiration (Farahani and DeCoursey, 2000). Soil temperature is computed by assuming that, during rainfall and irrigation events, the water passing through the soil carries heat energy proportional to the specific heat of water to deeper layers similar to piston displacement (Ahuja et al., 2000). During nonrainy periods, conduction of heat between soil layers also takes place

by solving the heat equation. Surface soil (1 cm) temperature is assumed to equal the average air temperature of the day. The soil C and N dynamics module contain two surface residue pools, three soil humus pools, and three soil microbial pools. Nitrogen mineralization, nitrification, denitrification, ammonia volatilization, urea hydrolysis, methane production, and other microbial processes are simulated in reasonable detail (Ahuja et al., 2000). Numerous studies have thoroughly tested and combined the RZWQM2 with field research conducted for managing dryland and irrigated cropping systems (Anapalli et al., 2005; Ma et al., 2003; Saseendran et al., 2004, 2005, 2008, 2009, 2010a, 2010b, 2013, 2014; Yu et al., 2006). Anapalli et al. (2016a, 2016b) successfully simulated cotton production systems in the humid climate of the Mississippi Delta with this model.

Our primary objectives of this study were to (i) quantify the relative performances of corn under NT and CT systems in the humid climate of the lower Mississippi Delta in field experiments and (ii) integrate experimental data in the RZWQM2 and develop management alternatives for combating the measured yield decrease under the NT.

## MATERIAL AND METHODS

### Corn Tillage Experiment

This experiment was conducted from 2008 to 2017 on a Dundee silt loam (fine-silty, mixed, active, thermic Typic Endoaqualfs) with less than 1% slope at Stoneville, MS (33.42°N, 90.92°W, 32 m asl) located in the lower Mississippi Delta region. The climate of the Mississippi Delta region was classified (Köppen–Geiger climate classification) as warm temperate and fully humid with hot summer (Kottek et al., 2006): on a mean monthly basis, there are no dry summers or winters, precipitation is evenly distributed throughout the year, the average monthly minimum temperature falls between  $-3^{\circ}\text{C}$  and  $+18^{\circ}\text{C}$ , and the maximum temperature is greater than  $22^{\circ}\text{C}$ . On an annual basis, the location received around 130 cm precipitation (Kebede et al., 2014; Anapalli et al., 2016a, 2016b). Normally, July and August are the hottest and driest months that can severely limit corn growth and productivity. For that reason, the farmers in the region plant corn in March and harvest it by August.

In 2007, both NT and CT fields were under cotton with CT practices. From 2008 onward, corn was ridge-planted with 102-cm row spacing in a north–south direction. Locally popular corn hybrids were planted in March and harvested in August (Table 1). The average seeding rate in the 9 yr was about 70000 seeds  $\text{ha}^{-1}$ . The crop was furrow-irrigated to replenish the soil water depleted in the past week back to field capacity, on the basis of soil water measurements. These irrigations were targeted to maintain the soil water content in the top 60 cm soil profile above 65% of the maximum plant available water. Because of irrigation well and pump operation difficulties, 4 cm of water was applied at each irrigation event. Nitrogen as urea ammonium nitrate was injected into the soil at the rate of 224 kg  $\text{ha}^{-1}$  at planting (Table 1). The experimental plots were on the farm scale: 1.5 ha with dimensions of 185 m in the north–south direction and 49 m in the east–west direction. The reasons for using farm-scale plots were: (i) to carry out all the soil–water–crop management operations similar to the farmers in the area, so that the knowledge gained from the experiment can be directly transferred to the local farmers with confidence; (ii) to

Table I. Major management practices applied to the no-till (NT) and conventional tillage (CT) experiments from 2009 to 2017.

Year	Hybrid	Planting date	Harvest date	Fertilization	Herbicide†	Tillage in CT plots	No of irrigations‡	Average grain yield	
								CT	NT
				kg N ha <sup>-1</sup>	No of applications			kg ha <sup>-1</sup>	
2009	P31G71LLRR	23 Mar.	27 Aug.	202 (UAN)	3 BP	CP, RT, RT	5	9,059a§	8,009b
2010	P31G71LLRR	24 Mar.	17 Aug.	224 (UAN)	4 BP 2 AP	CP, RT, RT CP	5	11,947a	10,950b
2011	P31G71LLRR	2 Mar.	12 Aug.	224 (UAN)	3 BP and 2 AP	RT, RT CP	2	7,650a	8,722a
2012	P33N55RR	19 Mar.	7 Aug.	224 (UAN)	5 BP and 1 AP	RT, RT MP	4	13,374a	12,214b
2013	P33N58RR	15 Mar.	26 Aug.	224 (UAN)	4 BP and 1 AP	RT, RT	1	13,565a	12,250b
2014	P33N58RR	20 Mar.	2 Aug.	224 (UAN)	4 BP and 1 AP	MP, RT, RT	1	14,636a	13,657b
2015	P33N58RR	27 Mar.	18 Aug.	224 (UAN)	4 BP¶ and 1 AP	CP, RT, RT	2	12,570a	10,252b
2016	DKC66-97	22 Mar.	8 Aug.	224 (UAN)	4 BP and 2 AP#	CP, RT, RT	2	10,467a	8,994b
2017	DKC66-97	21 Mar.	21 Aug.	224 (UAN)	4 BP and 1 AP	CP, RT, RT††	1	12,903a	10,871b

† The herbicides applied were Gramoxone (1,1'-dimethyl-4,4'-bipyridinium), glyphosate [(carboxymethylamino)methylphosphonic acid], Prowl [a.i. pendimethalin; 3,4-dimethyl-2,6-dinitro-N-(3-pentanyl)aniline], Dal II Magnum [a.i. S-metolachlor (2-chloro-N-[2-ethyl-6-methylphenyl]-N-[(2S)-1-methoxy-2-propanyl]acetamide)], Roundup (a.i. glyphosate), atrazine [6-chloro-N-ethyl-N'-isopropyl-1,3,5-triazine-2,4-diamine], 2,4-dichlorophenoxyacetic acid, Liberty [a.i. glufosinate-ammonium, ammonium (2S)-2-amino-4-(hydroxyl[methyl]phosphoryl)butanoate], Permit [a.i. halosulfuron-methyl (3-chloro-5-[[[4,6-dimethoxy-2-pyrimidinyl]amino]carbonyl]amino)sulfonyl]-1-methyl-1H-pyrazole-4-carboxylic acid methyl ester)], or Force 8.

‡ One extra spot spray of herbicide was applied.

§ Letters a and b: the same letter attached to data in both columns under NT and CT denotes no significant difference between average grain yields ( $P > 0.01$ ) and different letters denote a significant difference between average grain yields ( $P < 0.01$ ).

¶ Each irrigation amount was about 4 cm.

# One extra herbicide applied only in the NT plot.

†† CP, chisel plow; RT, ridge till; MP, moldboard plow; UAN: urea ammonium nitrate; BP: before planting ( includes both preplanting and pre-emergence applications); AP, after planting

avoid possible interactions between NT vs. CT plots that could have arisen out of the contrasting microclimates created by tillage-residue interactions via the heat-energy dynamics in these systems; and (iii) to provide reasonable fetch for instruments used for measuring canopy scale processes, for example, canopy temperature and evapotranspiration in the two systems.

The plots were divided into three replications in the east-west direction, across the rows of the plots. Grain yield data were collected from replicated NT and CT plots by harvesting four rows 185 m long with a combine (S690i Hillmaster Combine, John Deere, Moline, IL). We consider the experiment in 2008 (the first year) as an effort to prepare the land for the study, so data collected in this year were not used in this investigation.

Plant growth parameters such as leaf area index (LAI), plant height, and biomass were measured from replicated NT and CT plots. Soil samples were taken for the measurements of  $D_b$ , texture, and total C and N at depths of 0 to 15, 15 to 30, and 30 to 60 cm. All the soil properties were analyzed at the Agricultural Analytical Services Laboratory of the Pennsylvania State University, University Park, PA. The  $D_b$  of the soil at various depths was determined by the core method (Blake and Hartge, 1986). Water content and temperature in the 10-, 30-, and 60-cm soil layers were monitored using Stevens HydraProbe (Steven Water Monitoring Systems Inc., Portland, OR). Data were sampled every 1 min and averaged over 30 min and recorded on a data logger (CR-7X, Campbell Scientific Inc., Logan, UT). The LAI of corn was measured twice a week with a AccuPAR LP-80 Ceptometer (Meter Group Inc., Pullman, WA). Plant biomass samples were collected by removing plants in 1-m<sup>2</sup> areas twice during the crop season: one near the tasseling (R1 stage) and another at physiological maturity (R6 stage). All the plant measurements were replicated in 10 locations and soil samples at five random locations in each of the three replications of the NT and CT fields. Phenology observations were made visually and recorded every week.

### Data for the RZWQM2 Model

Daily weather data (solar irradiance, maximum and minimum temperature, wind speed, relative humidity, and precipitation) adequately representing the experimental location drive the model simulations. These data were obtained from the Delta Research and Extension Center, Mississippi State University's weather station at Stoneville, MS (within 1 km from the experimental location) (<http://www.deltaweather.msstate.edu>, accessed 3 Aug. 2018). Other essential inputs for the simulations are the soil physical and hydraulic parameters and crop and soil management information. The soil physical properties required are soil profile depth and horizons (layers), soil texture,  $D_b$ , and organic matter content. The soil hydraulic properties required are the water retention curves and the saturated hydraulic conductivity of each soil horizon represented in the form of Brooks and Corey equations. We did not have all these soil physical and hydraulic properties measured in the experiment, so they were estimated in the model from the measured soil texture,  $D_b$ , N, and C at 0- to 15-, 15- to 30-, and 30- to 60-cm depths. Since the soil texture across the location is predominantly silt loam, for simulations, we used the texture-based parameters developed by Rawls et al. (1982) for a silt loam soil.

Agronomic data collected included tillage dates and methods; dates, amounts, and methods of irrigation and fertilizer applications; and corn planting date, density, depth, and row spacing. The essential experimental data for calibration of the model for simulating a corn cultivar are grain yield, biomass at maturity, crop biomass, and LAI at different growth stages, phenology dates, and frequent soil water content measurements. All these data were collected from the field experiment.

To simulate a specific corn hybrid, the CERES-Maize 4.6 model requires six cultivar parameters (Jones et al., 2003). For simulation of the corn experiment, the RZWQM2 requires careful iterative calibration of its soil water component, followed by the N component, and finally the plant growth component

(CSM-CERES-Maize 4.6 model). In this study, we did not have to calibrate any of the soil water-related parameters in the RZWQM2. Soil parameters were estimated in the model from the measured soil texture and  $D_b$  for a silt loam soil (Table 2). The N-related parameters were also not calibrated as the simulations were reasonable. Therefore, we calibrated the cultivar parameters only, following Ma et al. (2011) (Table 3). Though three corn cultivars (P31G71LLRR, P33N55RR, and DKC66-97) were planted in the experiment, parameters were developed only for DKC66-97 and used in simulating all three cultivars (Table 1 and Table 3). This cultivar was selected for calibration, as it was the only one planted during 2016–2017 when the detailed crop data for model calibrations were collected. Crop phenology, LAI, grain yield, and crop biomass data collected in 2016 under both CT and NT systems were used in the calibration. The calibrated model was validated by simulating the soil surface residue fraction and mass under NT in 2015, 2016, and 2017; LAI and biomass under CT and NT in 2017; corn grain yield data measured from 2009 to 2017 under both NT and CT; and soil temperature at 10-, 30-, and 60-cm soil depths in 2017. As the model's performances during its calibration and validation periods did not differ much in accuracy, they are therefore presented together below.

### Statistics for Model Calibration and Evaluations

We evaluated the RZWQM2 calibration and validation results with the: (i) root mean squared deviation (RMSD) between simulated and measured values [Eq. 1], (ii) Relative RMSD (RRMSD), which varies between 0 and 100% [Eq. 2], and (iii) the mean deviation ( $MD$ ) between measured and simulated values [Eq. 3]:

$$RMSD = \sqrt{\frac{1}{n} \sum_{i=1}^n (P_i - O_i)^2}; \quad [1]$$

$$RRMSD = \frac{RMSE}{O_{avg}}; \quad [2]$$

$$MD = \frac{1}{n} \sum (P_i - O_i), \quad [3]$$

where  $P_i$  is the  $i^{\text{th}}$  simulated value,  $P_{avg}$  is the average of the simulated values,  $O_i$  is the  $i^{\text{th}}$  measured value,  $O_{avg}$  is the average of the measured values, and  $n$  is the number of data pairs.

Mean grain yields between NT and CT were compared with the single-factor ANOVA procedure available in the Microsoft Excel software (Microsoft Office Suite Professional Plus 2016, Microsoft, Redmond, WA) for significance ( $p < 0.01$ ).

## RESULTS AND DISCUSSION

### Observed Weather During the Experiment

Precipitation received during the nine corn seasons (planting to harvest, Table 1) from 2009 to 2017 at the location varied greatly between years (Fig. 1a). Sequentially from 2009 to 2017, seasonal precipitation amounts recorded were 71, 29, 32, 46, 50, 88, 51, 59, and 63 cm, respectively. Irrigation amounts applied during these crop season were 12, 24, 24, 16, 16, 12, 16, 16, and 16 cm, respectively (Fig. 1a). The daily lowest minimum

Table 2. Measured bulk density ( $D_b$ ) and Root Zone Water Quality Model† (RZWQM2) estimated water-holding capacities of the silt loam soil that was used in the simulations.

Soil depth cm	$D_b$ g cm <sup>-3</sup>	$\theta_s$ ‡	$\theta_{1/3}$ ‡	$\theta_{15}$ ‡
			cm <sup>3</sup> cm <sup>-3</sup>	
0–10	1.37	0.489	0.285	0.136
10–30	1.38	0.434	0.285	0.136
30–60	1.39	0.425	0.285	0.136
60–90	1.32	0.501	0.285	0.136
90–120	1.40	0.431	0.285	0.136

† The model estimated  $h_b$  (the air entry water suction) and  $\lambda$  (the pore size distribution index) by fitting the Brooks–Corey equation to the data given in the table for obtaining the soil water retention curve.

‡  $\theta_s$ ,  $\theta_{1/3}$  and  $\theta_{15}$  are soil water contents at field saturation, field capacity (drained upper limit), and plant wilting point (drained lower limit), respectively.

and highest maximum temperatures recorded were, 2.8 and 37.8°C in 2009, 2.2 and 37.7°C in 2010, 1.7 and 38.3°C in 2011, 13.9 and 38.8°C in 2012, –1.18 and 34.4°C in 2013, –0.57 and 35.6°C in 2014, 3.9 and 38.6°C in 2015, 1.6 and 36.2°C in 2016, and 0.0 and 34.4°C in 2017 (Fig. 1b). Within the corn season, all the daily lowest minimum temperature events occurred in March and all the highest maximum events occurred in July.

### Effect of Tillage on Corn Production

Under CA, NT and minimum tillage carry higher potential for raising crops with minimum soil disturbance and consequent better soil–water–air qualities (Busari et al., 2015). On the other hand, tilled fields provide modest soil physical conditions for better root development and consequent enhancements in nutrient and water uptake, resulting in better crop yields. Past studies in many regions across the world have reported that long-term NT management resulted in improvements in soil organic matter content, increased water infiltration into the soil, reductions in soil erosion, reductions in greenhouse gas emissions, and reductions in input costs for tillage operations across climates and soils; however, impacts on crop grain yield per se varied with various climate, soil, and landscape conditions (DeFelix et al., 2006). In our experiment from 2009 to 2017, except for 2011, corn grain yields from the NT system were significantly ( $P < 0.01$ ) lower than grain yields from the CT system (Table 1). On average, NT produced 9% less grain yield than under CT. In 2011, the grain yield under NT was higher than CT by 14%; however, this difference was not statistically significant ( $P > 0.01$ ) owing to the high variability in the measured grain yields across the field replications: the SD in measured grain yield was 1476 kg ha<sup>-1</sup> under NT and 717 kg ha<sup>-1</sup> under CT. In general, rainfall received during the crop season did not correlate well with the irrigated corn yields in this study. However, corn grain harvested across the 9 yr under CT showed relatively better correlations with seasonal rainfall (Karl–Pearson coefficient of correlation,  $r = 0.35$ ) than grain harvested under NT ( $r = 0.25$ ). This shows that in the fully irrigated corn production scenario in our experiments with similar N inputs between CT and NT, the measured decline in grain yield production under the NT system are likely to be caused by additional factor or factors that were or were not affecting grain production in the CT system, which warrants further investigation. In Tennessee, in

Table 3. Calibrated plant parameters used for simulating corn hybrids in the tillage experiments at Stoneville, MS, from 2009 to 2017.

Acronyms used	Definitions of traits	Parameter values
P1	Degree-days (base temperature of 8°C) from seedling emergence to end of the juvenile phase (thermal degree-days).	260
P2	Day length sensitivity coefficient: the extent (in days) that development is delayed for each increase in photoperiod by 1 hr above the longest photoperiod (12.5 h) at which development proceeds at maximum rate.	0.12
P5	Degree days (base temperature of 8°C) from silking to physiological maturity (thermal degree-days)	1130
G2	Potential kernel number	880
G3	Potential kernel growth rate (mg kernel <sup>-1</sup> d <sup>-1</sup> )	9.20

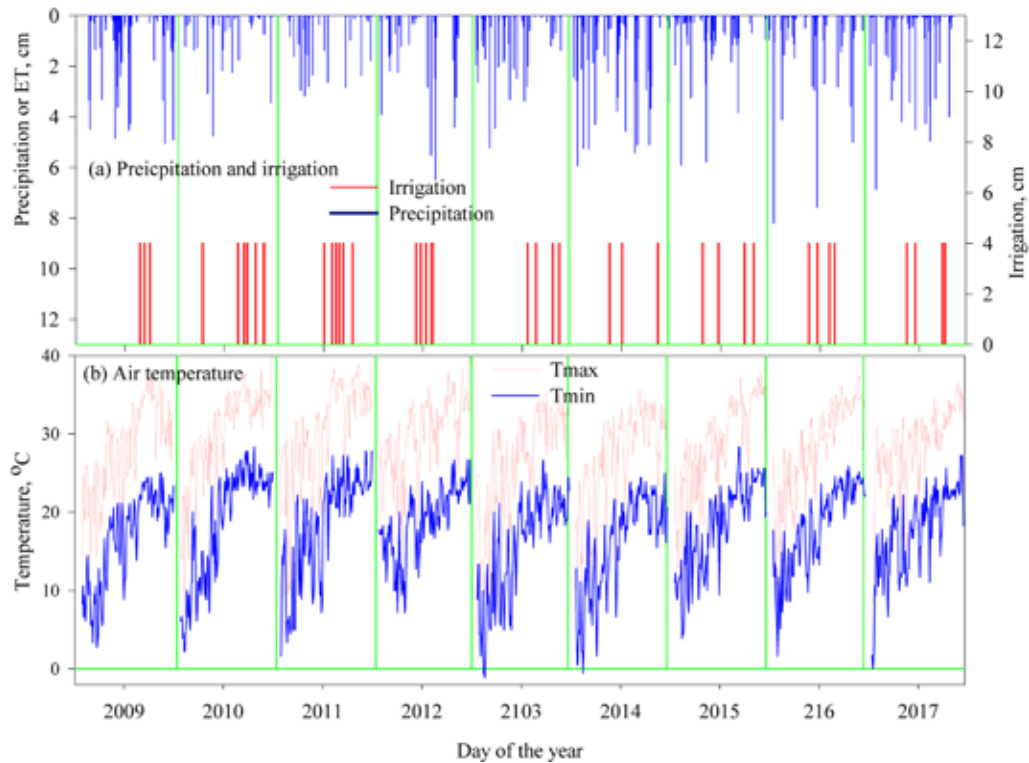


Fig. 1. Observed rainfall, irrigation applied, and maximum and minimum air temperatures during the corn growth season (April–August) from 2009 to 2017.

a 3-yr study, NT produced 28.9% more corn grain yield than CT, probably because of higher soil water conservation under NT during drought periods, as the crops were not sufficiently irrigated (Yu et al., 2016). In our experiments, whenever the rainfall received was not enough to support soil water above ~65% of plant-available water content, we irrigated the crops with enough water to replenish the soil back to its field capacity, so we expect enough soil water to have been available under both the NT and CT systems (Table 1, Fig. 1).

Data collected in our experiment from 2009 to 2015 were mainly confined to the crop–soil–water management data and harvested grain yields. Obviously, these data are insufficient for investigating if the reason for the measured grain yield decreases under NT were caused by water, N, or other deficiencies in this system compared with the CT system. To get a continuous picture of N and water dynamics in both the NT and CT systems for a comparative and extensive analysis of various factors that may have contributed to the measured yield behavior, we measured corn phenology, biomass growth measured two or three times a year, twice-weekly LAI, and soil water and temperature at soil depths of 10, 30, and 60 cm in 2015 and 2017.

The measurements in 2017 showed that water in the soil, as expected, were significantly ( $P < 0.01$ ) higher under NT than under CT, with the exception of a few days at the 60-cm soil depth, resulting from the suppression of evaporation from the soil by residue cover (discussed below) (Fig. 2a–c). On average, soil water contents varied between 0.22 and 0.43, 0.24 and 0.47, and 0.24 and 0.48 cm<sup>3</sup> cm<sup>-3</sup> at soil depths of 10, 30, and 60 cm, respectively, under NT. Soil water contents under CT ranged from 0.19 to 0.45, 0.26 to 0.45, and 0.34 to 0.46, respectively, at 10, 30, and 60 cm. On average, volumetric soil water under NT was higher by 0.063 at 10 cm, 0.047 at 30 cm, and 0.044 cm at 60 cm. At the 60-cm soil depth, soil water under NT at the beginning of the crop season was lower than that under CT for about 30 d, but afterwards, the trend was reversed (Fig. 2c). Despite this higher measured soil water under NT, corn grain harvested in this system was consistently lower than the yields produced under CT; based on this, we hypothesized that some other factors limited corn productivity under the NT system. Our observations on the various parameters we examined in search of a stable causative factor for the measured yield decrease under the NT system are discussed below.

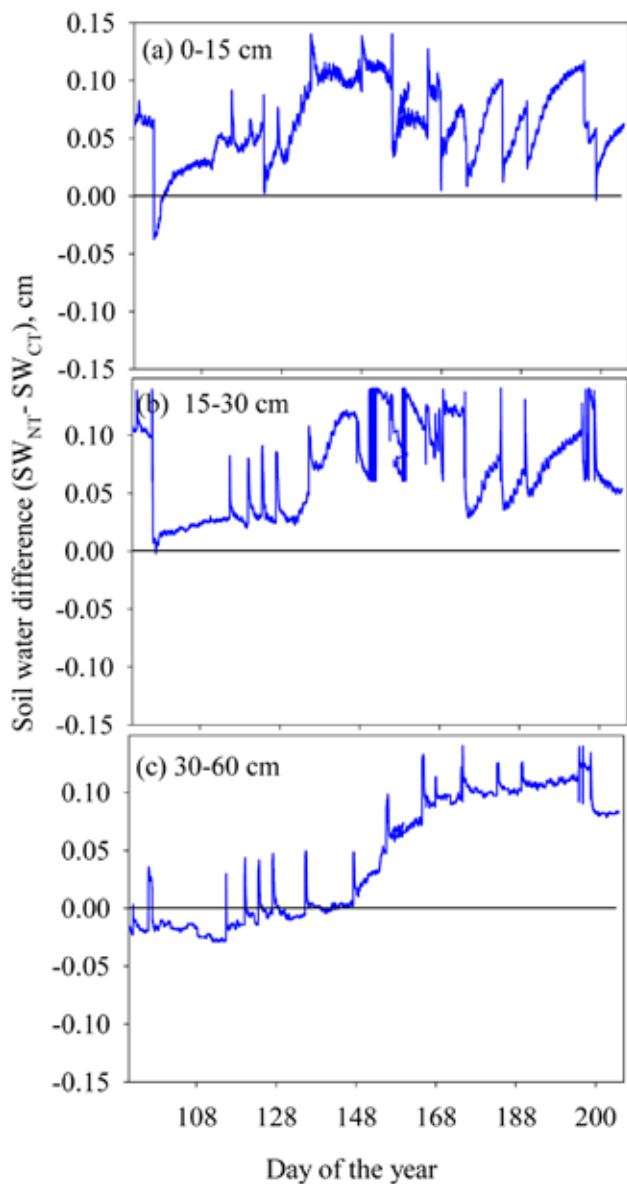


Fig. 2. Measured soil water difference between no-till (NT) and conventional tillage (CT) systems ( $SW_{NT} - SW_{CT}$ ) under corn at 0- to 15-, 15- to 30-, and 30- to 60-cm soil depths in 2017, where  $SW_{NT}$  is the measured soil water under NT and  $SW_{CT}$  is the measured soil water under CT.

### Impact of Soil Bulk Density Changes

After 8 yr of NT land management, soil  $D_b$ , as measured on 23 Sept. 2016 was relatively higher than those measured under CT (Fig. 3a):  $D_b$  under NT was 1.49, 1.50, and 1.41  $\text{g cm}^{-3}$  at 0- to 15-, 15- to 30-, and 30- to 60-cm soil depths, respectively, and those measured under CT were 1.38, 1.40, and 1.42  $\text{g cm}^{-3}$ , respectively. The measured difference in  $D_b$  between NT and CT were not statistically significant ( $P > 0.01$ ) at the 0- to 15- and 30- to 60-cm depths. However, the 0.10  $\text{g cm}^{-3}$  higher  $D_b$  measured under NT than under CT at the 15- to 30-cm soil depth was statistically significant ( $P < 0.01$ ). Averaged across the 0- to 15-, 15- to 30-, and 30- to 60-cm depths, the increase in  $D_b$  under NT in 9 yr in our experiment was 6%. The  $D_b$  averaged across the 30- to 60-cm soil depth under CT was 1.39  $\text{g cm}^{-3}$  and that under NT was 1.47  $\text{g cm}^{-3}$ . Mangalassery et al. (2014) reported an increase in  $D_b$  under NT in a 9-yr experiment in East Midlands of the U.K. Heard et al. (1988), however,

reported lower  $D_b$  in NT systems than in plowed plots at 20- to 30-cm soil depths. In a 2-yr study, You et al. (2017) reported no significant effect of increased  $D_b$  and compaction on spring corn yield in China. In the Argentine Pampas, in general, increases in  $D_b$  under NT were negligible, averaging about 4% (Alvarez and Steinbach, 2009). On the basis of field studies and reviews of the literature, Hassan et al. (2007) and Hamza and Anderson (2005) reported that crop root growth in the soil is suppressed only when soil BD reaches above 1.5  $\text{g cm}^{-3}$ . On the basis of the studies reported in the literature, and from the fact that the measured BD in our experiments stayed within 1.5  $\text{g cm}^{-3}$  and was statistically similar for CT and NT at two out of three depths (Fig. 3), we conclude that BD change was not a contributing factor to the measured yield decrease under the NT system.

### Impact of Plant Density and Seeding Emergence

Changes in plant density can adversely affect crop yield. Under NT systems, in the poorly drained soils in Iowa, a loss in plant density associated with slower seedling emergence from the soil was reported to produce lower corn grain yields (Mock and Erbach, 1977; Carter and Barnett 1987). In our experiments, the average plant density as counted on 10 June 2016 was 7.84 plants  $\text{m}^{-2}$  (SD = 0.64 plants  $\text{m}^{-2}$ ) under CT and 7.86 plants  $\text{m}^{-2}$  (SD = 0.78 plants  $\text{m}^{-2}$ ) under NT (the difference was not significant;  $P > 0.01$ ). On 24 July 2017, the corn plant density counted under CT was 9.43 plants  $\text{m}^{-2}$  (SD = 0.75 plants  $\text{m}^{-2}$ ) and was 10.00 plants  $\text{m}^{-2}$  under NT (SD = 1.41 plants  $\text{m}^{-2}$ ); this difference was also not statistically significant ( $P > 0.01$ ). From these, it appears that plant density was not a critical factor in reducing the yield in the NT system.

The number of days taken for the corn seedling emergence in both 2016 and 2017 did not show any appreciable differences between the NT and CT systems: under both NT and CT, seedling emergence took place 8 d and 6 d after planting, respectively, in 2016 and 2017 (data not shown). It is important to point out that adoption of up-to-date technological advances in planting (drilling) at uniform depths, weed control with more effective herbicides, and use of herbicide-resistant corn cultivars in our experiment had overcome most of the problems associated with corn stand establishment in NT systems. In addition, to account for the residue accumulation on the soil in the NT plots, we adjusted planter settings to plant an inch deeper than in CT soils that had negligible residue cover.

### Total Carbon and Nitrogen in the Soil

Measured C contents on 16 June 2017, at the 0- to 15-, 15- to 30-, and 30- to 60-cm soil depths under CT were higher than those under NT; however, these differences were statistically significant ( $P < 0.01$ ) only at 0 to 15 cm (Fig. 3b). This contrasts with the consensus that crop residue accumulation and lack of soil disturbance from NT management results in more C build-up in the surface soil layer. Conventional tillage either causes greater loss of C from the soil or redistributes C to deeper soil layers (Jagadamma and Lal, 2010; VandenBygaart et al., 2003; Blanco-Canqui and Lal, 2008). As our soil C measurements in response to tillage treatments at the surface (0–15 cm) layer differed from others reported in the literature, we collected another set of independent soil samples and reanalyzed those and confirmed our findings with consistent results.

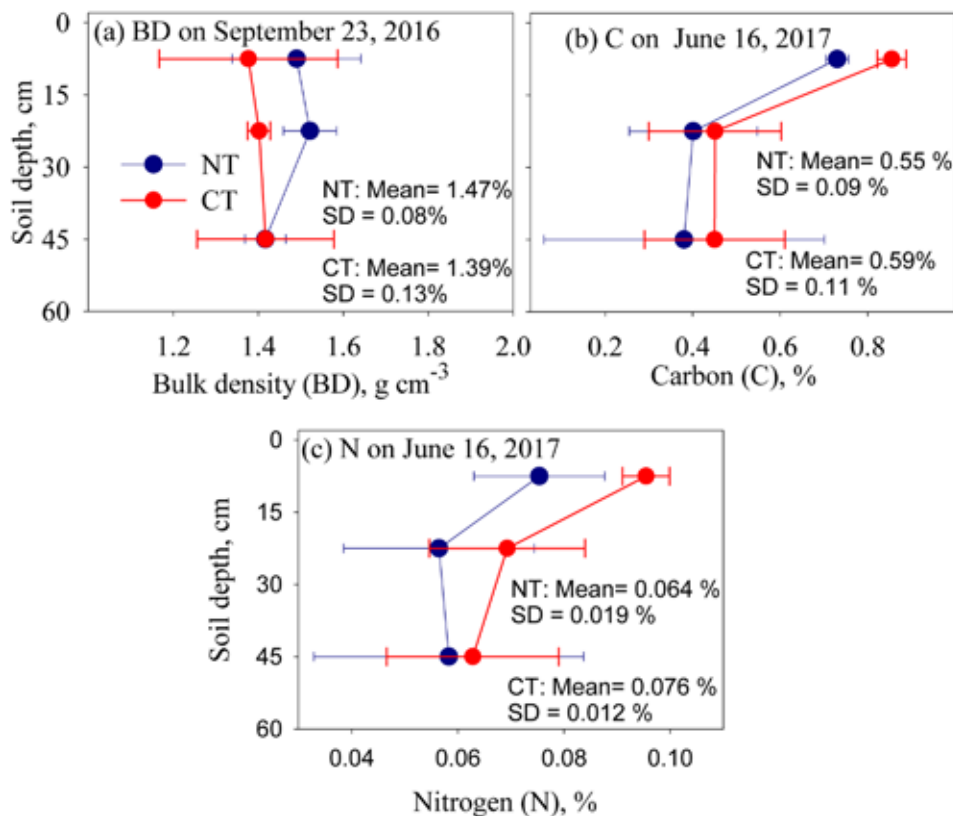


Fig. 3. Measured soil (a) bulk density (BD) on 23 Sept. 2016, (b) total C on 16 June 2017, and (c) total N on 16 June 2017 at 0- to 15-, 15- to 30-, and 30- to 60-cm depths under no-till (NT) and conventional tillage (CT) systems. Mean and SD are averaged across soil depths.

The total N (inorganic + organic) measured at soil depths of 0 to 15, 15 to 30, and 30 to 60 cm on 16 June 2017 was higher under CT than under NT (Fig. 3c). The amounts of N measured, however, exhibited higher variability across replications, as reflected in the error bars in Fig. 3c. Total N averaged across all the three depths under NT and CT was 0.064% (SD = 0.019) and 0.076% (SD = 0.012%), respectively. The measured N values under NT and CT were not significantly different ( $P > 0.01$ ) from each other, except at 0 to 15 cm.

### Investigating Possible Reasons for the Measured Corn Yield Decrease under No Tillage

From these results, it appears that the only measured factors that could potentially have caused the measured yield decrease in the NT system were the reduced C and N availabilities under that system compared with the CT system. However, we did not measure all the components of N and C dynamics (e.g. labile C versus total C, N loss to runoff and leaching, and N mineralization and denitrification) in the NT and CT systems to establish cause-effect relationships for the observed yield decrease. Moreover, the field data were collected in a limited number of years. In this context, we simulated the impacts of our NT and CT land management practices on crop yield, soil surface residue cover, water (soil water, evapotranspiration, infiltration, runoff, and deep percolation), and N (N mineralization and nitrification; and N loss to runoff, deep percolation, and denitrification) dynamics via the RZWQM2.

Detailed phenological growth stages of the crops were observed from the beginning of the experiment in 2009. However, data records were available only from 2015 to 2017 for

Table 4. Measured and simulated silking and physiological maturity days for corn in the tillage experiments in 2015, 2016, and 2017.

	Measured DOY‡	Measured DAP‡	Simulated DAP‡	Error (s - m)
2015				
Planting	86	0		-3
Silking	155	69	66	-3
Maturity†	212	126	123	
2016				
Planting	82	0		4
Silking	157	74	72	-2
Maturity†	214	132	130	
2017				
Planting	80	0		1
Silking	147	67	66	-3
Maturity†	210	130	127	

† Maturity = physiological maturity.

‡ DOY, day of the year; DAP, d after planting; s, simulated; m, measured.

analysis (Table 4). In the 9 yr of the experiment, the phenological growth stages of corn under the CT and NT systems were identical. In the cropping seasons of these 3 yr, planting occurred between March 21 and 27, silking occurred between 67 and 74 d after planting, and physiological maturity occurred between 126 and 132 d after planting (Table 1 and Table 4). In these years, the deviations between the simulations and field-measured number of days for the corn plants to reach the silking and physiological maturity stages of growth varied between -3 to 4 d (Table 4).

Simulations of LAI under both CT and NT in both 2016 and 2017 had similar accuracies: the RMSDs of the simulations were between 0.49 and 0.70, the relative RMSDs were between 15 and 23%, and MD were between 0.43 and 0.63 (Fig. 4a-d). There

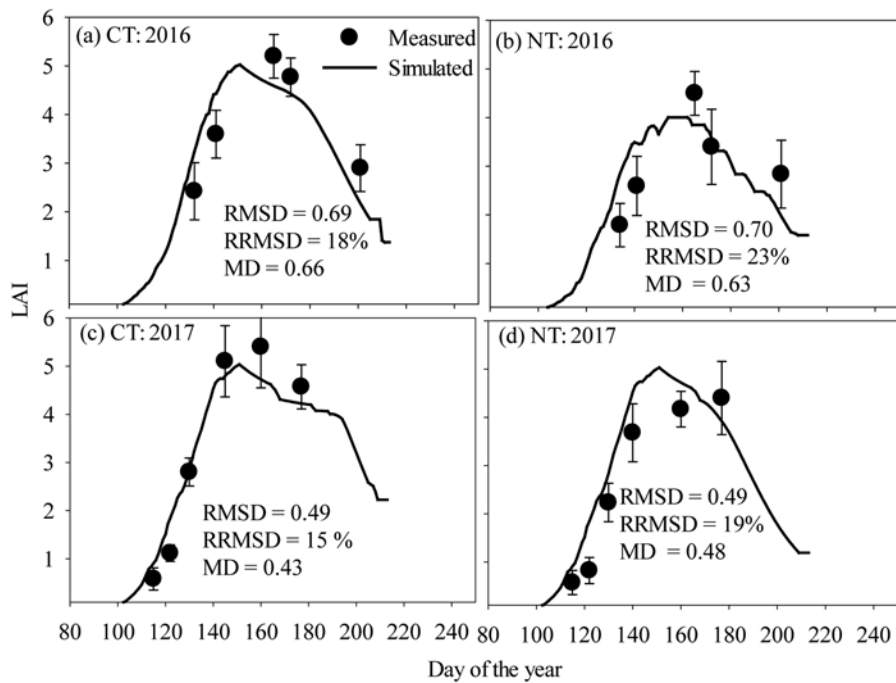


Fig. 4. Comparison between the measured and simulated corn leaf area index (LAI) in 2016 and 2017 crop seasons. Error bars indicate 1 SD in the measurements. RMSD, the root mean squared deviation; RRMSD, relative RMSD; MD, mean deviation.

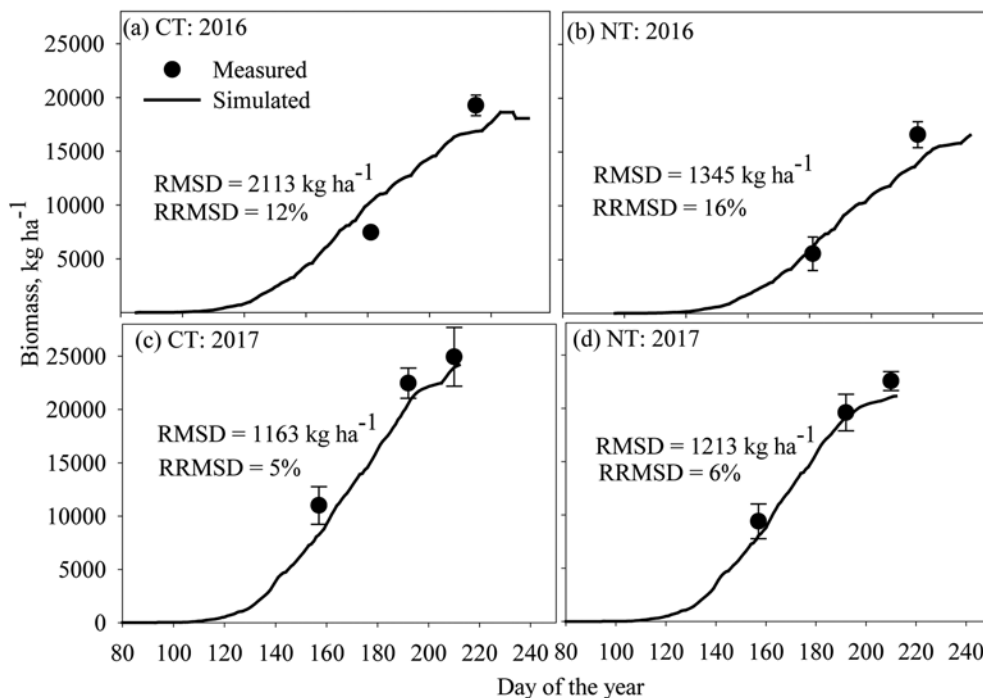


Fig. 5. Measured and simulated corn biomass under no-till (NT) and conventional tillage (CT) systems in 2016 and 2017: (a) CT in 2016, (b) NT in 2016, (c) CT in 2017, and (d) NT in 2017. Error bars indicate 1 SD in the measured data. RMSD, root mean squared deviation; RRMSD, relative RMSD; MD, mean deviation.

were considerable variations in the measured LAI across measurement replications in the field, as reflected in the length of the error bars in Fig. 4a–d; notwithstanding, most of the simulated LAI values were within or close to 1 SD (Fig. 4 a–d) of the measurements. The MD of the simulations of corn biomass in 2016 under CT was  $2113 \text{ kg ha}^{-1}$  (RMSD = 12%) and that under NT was  $1345 \text{ kg ha}^{-1}$  (RMSD = 16%) (Fig. 5a,b). In 2017, the MDs of the simulations were  $1163 \text{ kg ha}^{-1}$  (RMSD = 5%) and  $1213 \text{ kg ha}^{-1}$  (RMSD = 6%), respectively under CT and NT (Fig. 5c,d).

Overall, the performance of the crop biomass simulations reflected the required potential of the model for its application in simulating the different performances of NT and CT for the climatic conditions of the study location. After each crop harvest, the generated crop biomass was left as crop residue on the surface of the soil under the NT treatment, and they were incorporated into the soil by tillage in the CT treatment. The crop residues were further subjected to the subsequent C and N cycling processes in the system in response to the actual weather and management.



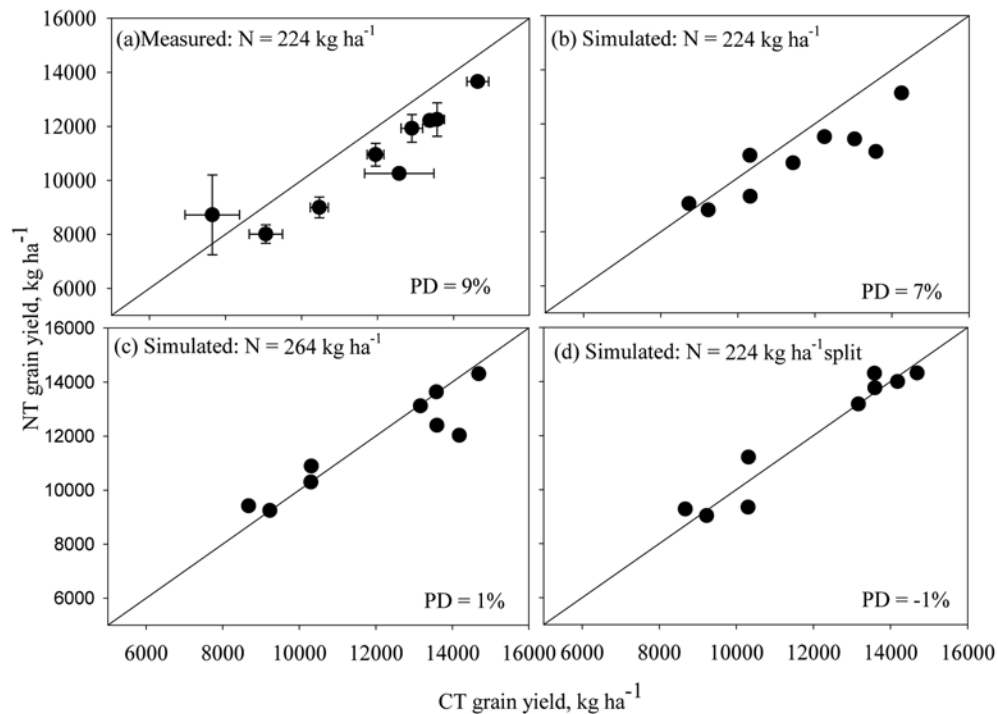


Fig. 6. Measured and simulated corn grain yields between no-till (NT) and conventional tillage (CT) systems (1:1 plot) from 2009 and 2017: (a) measured yields (N inputs were at  $224 \text{ kg ha}^{-1}$ ), (b) simulated yield with N inputs being the same as measured, (c) simulated grain yields with N application at  $264 \text{ kg ha}^{-1}$ , and (d) simulated grain yield in response to split N ( $50 \text{ kg ha}^{-1}$  at planting and  $174 \text{ kg ha}^{-1}$  on 14 May). Horizontal and vertical error bars indicate 1 SD in the measured corn yield under CT and NT, respectively. PD, percentage decrease in yield under NT.

As discussed above, harvested grain yield measurements were higher under CT than NT in all but 1 out of 9 yr; therefore, all but one of the NT grain yield plotted points in Fig. 6a were below the 1:1 line. In the simulations, seven out of nine harvested grain yields were higher under CT than under NT (Fig. 6b). Apart from 2011, the grain yield under NT in 2009 was also higher than under CT by 5% because of the relatively lower N stress simulated under the NT system in this year (data not shown). However, as the error in this simulated grain yield was only 5%, it cannot be taken as a serious deterrent to applying the model for further investigation of the system. It was seen from the simulations that the main reason for lower grain yields under NT was the consistently higher N stress for the crop in this system, compared with N stress under the CT system. Water stress simulated in both the systems did not differ appreciably, as water received through rainfall or irrigation was sufficient in both the systems for ample plant uptake and stress-free growth. As discussed above, lower N amounts, though statistically significant at 0 to 15 cm only, were measured under the NT treatment compared with the CT treatment. Therefore, further investigations of N and C dynamics in the systems were required to ascertain the causes of the higher simulated N stress and lower measured N amounts under the NT treatment when identical amounts of N were applied in both systems.

For accurate simulations, C and N dynamics in the soil, the RZWQM2 should be able to model crop residue dynamics accurately in and on the soil surface in response to tillage. Simulations of the soil surface crop residue cover fraction under NT in 2015, 2016, and 2017 were within 1 SD of the experiment replications (Fig. 7a). The measured and simulated values, respectively, were 0.89 and 0.92 on 9 Mar. 2016, 0.85 and 0.91

on 21 Mar. 2016, and 0.90 and 0.92 on 12 Dec. 2017. The soil surface crop residue mass corresponding to the crop residue covers were also simulated within or close to 1 SD of the measured values across replications (Fig. 7b). Measured crop residue mass on 9 Mar. 2016, 21 Mar. 2016, and 12 Dec. 2017 was, respectively,  $10,051$ ,  $12,288$ , and  $14,011 \text{ kg ha}^{-1}$  and the corresponding simulated values were  $14,986$ ,  $13,431$ , and  $15,308 \text{ kg ha}^{-1}$ . On these days, there was no appreciable crop residue observed on the soil surface under the CT system, as the residue left on the soil surface after harvest was incorporated into the soil by the subsequent tillage events during the fall season (tillage events are given in Table 1). The simulations also showed no residue on the soil surface that was not incorporated into the soil matrix (Fig. 7b). In the experiments, we did not have measurements of crop residue mass in the soil (inside the soil matrix), so we could not verify the simulation's accuracy in this respect. However, the simulations reflected residue incorporation into the soil matrix with each tillage event and its subsequent decomposition under CT (Fig. 7b,c). Because residues were incorporated into deeper layers in the soil profile under CT, on an average relative basis, the biomass available for decomposition in the 120-cm soil profile was 7% higher than the residue mass under NT (Fig. 7c).

The temperature of the soil is important in the mineralization of organic matter and subsequent availability of N for crop uptake. Thus it is equally important that the model used in investigating N dynamics is also able to simulate soil temperature accurately. When we had a continuous simulation of soil temperature from 2009 to 2017 on a daily time step, continuous whole-season measurement of soil temperature was available only in 2017 for comparison with those simulations (the 2016 measurements had problems arising from animal attack). The

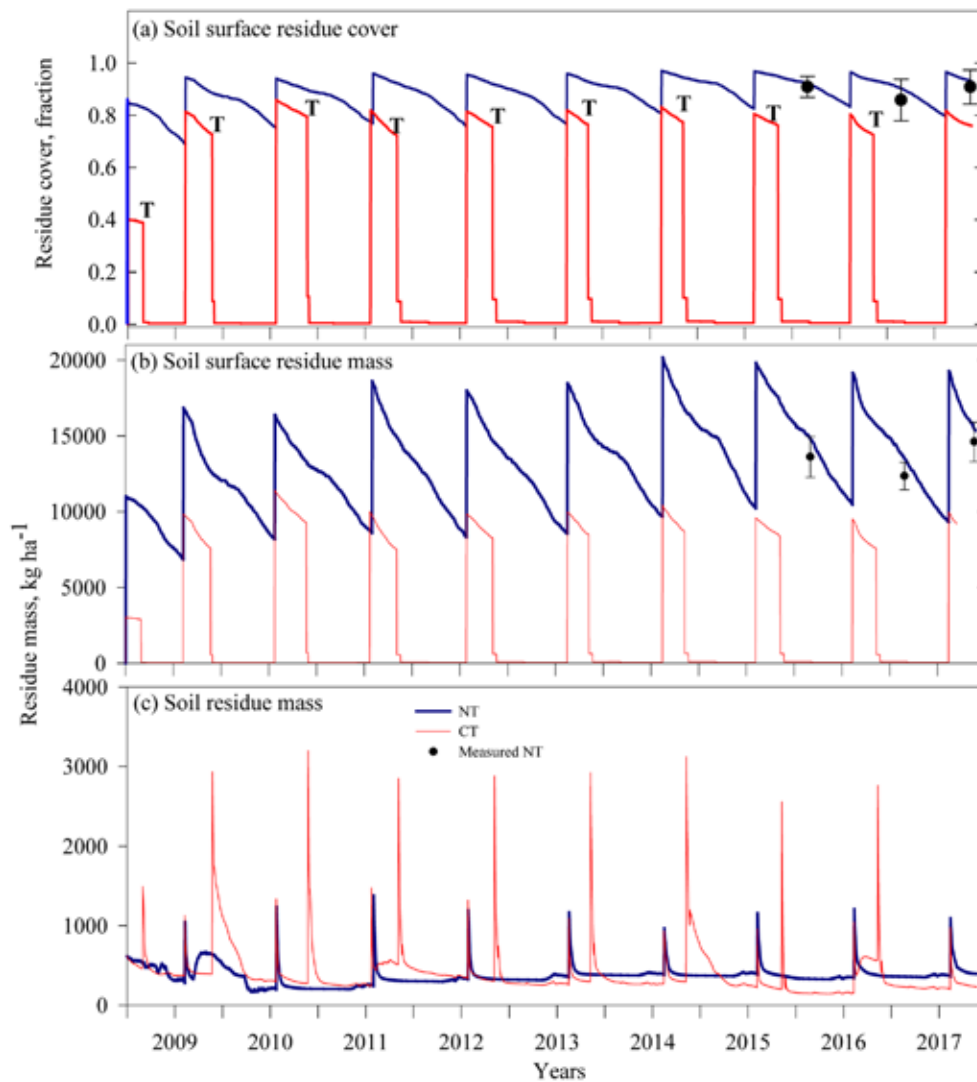


Fig. 7. Measured and simulated corn residue dynamics in the no-till (NT) system under corn from 2009 to 2017: (a) soil surface residue cover, (b) soil surface residue mass, and (c) soil residue mass in the 120-cm soil profile. T = major (subsoil) tillage event.

measured soil temperatures at 10, 30, and 60 cm under the NT were lower than those under CT. As the soil surface under NT always had 80 to 100% covered by the crop residue, very little sunlight could enter the soil directly, leading to the lower temperature under this treatment. The simulated average daily soil temperature at 10, 30, and 60 cm deviated significantly ( $P > 0.01$ ) from the measured values (Fig. 8a–c). However, the lower soil temperature measured under NT than under CT was simulated well (the value of the soil temperature under NT minus the soil temperature under CT was negative; Fig. 8a–c).

Furthermore, the investigation revealed that the amount of N mineralized was consistently lower under NT than under the CT system, mainly in response to the lower soil temperature (Fig. 9a). Residue mineralization can provide a continuous supply of available N and other nutrients for plant uptake (Sarker et al., 2018). Hence, a lower mineralization rate possibly reduced corn productivity under the NT because of the lower crop N uptake under this system than under the CT system. The two most important abiotic factors influencing N mineralization in the soil are soil water and temperature (Leirós et al., 1999). From the discussions above, we could conclude that soil water was not a limiting factor under NT. However, lower

mineralization in response to the lower soil temperature might have limited yield under the NT system.

Further investigations of the simulated data revealed that the denitrification rates, N leached below the root zone, and N in runoff during all nine crop seasons (2009–2017) under NT were significantly ( $P < 0.01$ ) higher. These higher losses of N from the system led to further deterioration of the already reduced N available for crop uptake in this system (Fig. 9b–d). From both measurements and simulations, it seems that the substantially higher soil water content under the NT system was the main factor causing the higher denitrification under NT (Fig. 3 and Fig. 10b). Increased water infiltration into the soil and lower loss of water through evapotranspiration were also simulated under NT compared with CT, which contributed to greater retention of soil water under NT (Fig. 10b,d). To explain the simulated higher N loss through runoff and percolation, we did not have either a measurement of the amount of water lost to runoff and deep percolation in the system or the concentration of N in the waters. Therefore, we examined the differences in the simulated amounts of runoff and deep percolation of water from the NT and CT systems: Losses of water caused by both runoff and deep percolation processes were significantly

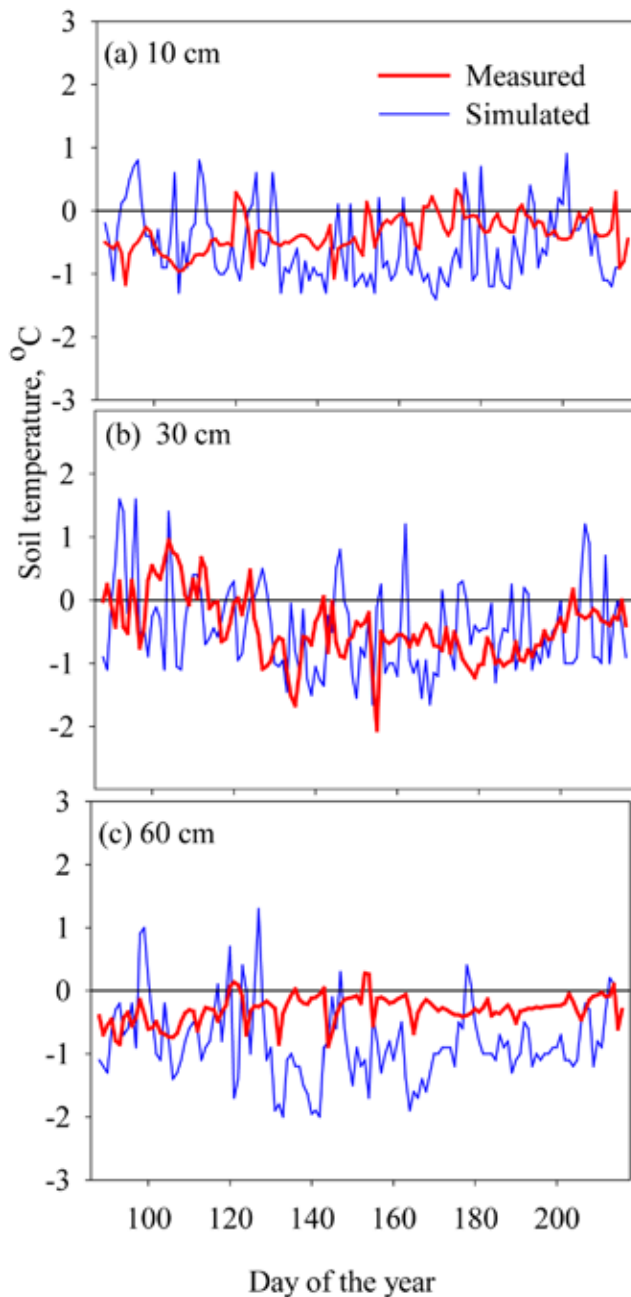


Fig. 8. Measured and simulated soil temperature difference between no-till (NT) and conventional tillage (CT) ( $T_{NT} - T_{CT}$ , where  $T_{NT}$  is soil temperature under the NT treatment and  $T_{CT}$  is soil temperature under the CT treatment) at soil depths of 0 to 15, 15 to 30, and 30 to 60 cm in 2017.

( $P < 0.01$ ) higher under NT than under CT (Fig. 10a,c). Both these enhanced water flows out of the system also transported more dissolved N out of the NT system.

From the above results and discussions, it is clear that the corn crop under the NT system did not benefit from the measured higher water conservation under NT systems. The main reason for this, as brought out from the results presented above, was the lower N availability for plant uptake under NT caused by a lower N mineralization rate and the greater loss of N to runoff and deep percolation of water than under the CT system. This lower N uptake obviously resulted in reduced corn grain production in the NT system compared with the CT system. Unfortunately, we did not have measurements for crop N uptake to verify this

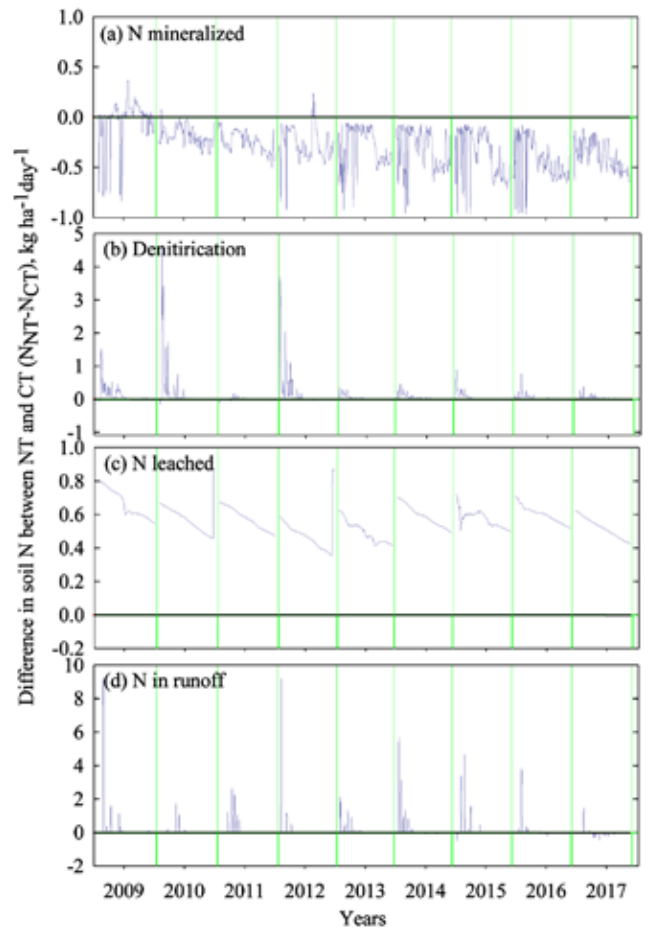


Fig. 9. Simulated differences in N in the soil between no-till (NT) and conventional tillage (CT) ( $N_{NT} - N_{CT}$ , where  $N_{NT}$  is N under NT and  $N_{CT}$  is N under CT) under corn during the corn growth periods from 2009 to 2017: (a) N mineralized, (b) denitrification, (c) N leached, and (d) N in runoff.

because of some technical problems related to bad weather and wet soil towards the end of the crop season. We investigated further to evolve an N management plan for the NT system that has the potential to ameliorate the lower N availability and produce grain yields on par with the CT system. In this direction, we simulated the crop with N application at levels 20, 40, and 60  $\text{kg ha}^{-1}$  higher than the current level of 224  $\text{kg ha}^{-1}$  at planting. These simulations showed that by enhancing the current N application level by 40  $\text{kg ha}^{-1}$  above the current level, seven out of nine measured grain yields under NT could be brought to grain yield levels close to or above those obtained under the CT system (Fig. 6c). The percentage difference [ $(\text{grain yield under NT} - \text{grain yield under CT}) \div \text{grain yield under the NT} \times 100$ ] between the simulated grain yield under NT and CT from 2009 to 2017 with this N level (264  $\text{kg ha}^{-1}$ ) was 1% (Fig. 6c).

We also recognize that enhancing the amount of N applied to crops can also lead to increased losses to runoff and deep percolation, as seen under the NT system in the simulations above, further enhancing the environmental impacts of the NT system. Thus we investigated possible grain yield returns in response to split applications of the current level of N with 25, 50, 75, and 100  $\text{kg ha}^{-1}$  at planting and the remaining N amounts on 7, 14, 21, and 28 May of the year the crops were planted. Simulations revealed that a split application with

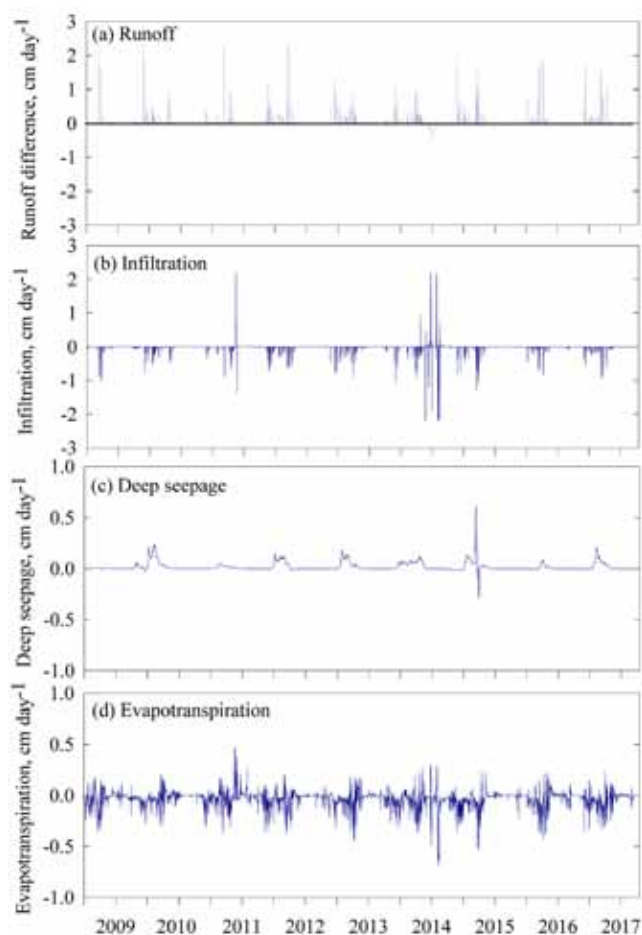


Fig. 10. (a) Simulated differences in water dynamics between no-till (NT) and conventional tillage (CT) (amount of water in the soil under NT minus the amount of water in the soil under CT) under corn from 2009 to 2017: differences in amount of water caused by (a) runoff, (b) infiltration, (c) deep percolation, and (d) evapotranspiration.

50 kg N ha<sup>-1</sup> at planting and the remaining 174 kg N ha<sup>-1</sup> on 14 May would make grain yields under NT comparable to those obtained under CT (Fig. 6d). The percentage difference of simulated grain yield resulting from this management from 2009 to 2017 was -1%. On average, because of the split N applications, N loss in deep percolation and runoff water decreased by 14 and 4 kg ha<sup>-1</sup>, respectively. However, in the case of enhancing the N application by 40 kg ha<sup>-1</sup>, N loss to deep percolation increased by 3 kg ha<sup>-1</sup> and N loss to runoff water increased by 1 kg ha<sup>-1</sup>.

## CONCLUSION

In this study, we investigated the different effects of NT and CT land management practices on corn production in a humid climate of the lower Mississippi Delta. Except for the soil tillage operations under the CT, all the soil-water-crop management practices were as followed by the local farmers in the region. The plot sizes (1.5 ha) of the experiment also represented a field management unit for irrigation within the bigger farms in the region. Under NT, total soil N and C; corn biomass, LAI, grain yield, and soil temperature were lower and soil water was higher than those measured under CT. Averaged over the nine crop seasons, a 9% reduction in corn grain yield under NT was measured. Further, we investigated the possible reasons for the

measured lower N availability and associated reduced corn yield under NT by integrating the experiments with the RZWQM2 and explored alternative N management possibilities that compensated for these problems. On the basis of the measurements and simulations, we concluded that the N loss to runoff and deep percolation, denitrification caused by higher soil water content, and a low N mineralization rate caused by lower soil temperatures under NT potentially contributed to the observed grain yield decrease under this treatment. In the humid climate of the Mississippi Delta, the known water conservation effects of NT were not seen to help the growth of irrigated corn crops in this experiment. An additional N application of 40 kg ha<sup>-1</sup> at planting, or a split application of the current N rate (224 kg ha<sup>-1</sup>) with 50 kg ha<sup>-1</sup> at planting and the remaining 174 kg ha<sup>-1</sup> in the second week of May were found to compensate for the lower N availability under NT and to maintain yield returns comparable to those measured under the CT system. Field testing of this N management alternative for enhancing productivity under NT will be verified in experiments in the coming seasons.

## CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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