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SOIL RESEARCH

Simulation of maize and soybean yield using DSSAT under long-term conventional and no-till systems

Teerath Rai[A,B,*], Sandeep Kumar[B], Thandiwe Nleya[B], Peter Sexton[B] and Gerrit Hoogenboom[C]

For full list of author affiliations and declarations see end of paper

***Correspondence to:**
Teerath Rai
Department of Crop Sciences, University of Illinois, Urbana-Champaign, Champaign, IL, USA
Email: tsrai@illinois.edu

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ABSTRACT

Context. No-tillage (NT) has been gaining popularity over the conventional tillage (CT) for agricultural sustainability. Field experiments conducted worldwide to compare crop production under NT vs CT systems are generally site specific and expensive to maintain over longer duration. To overcome this gap, process-based models have been used to simulate the potential impact and benefits of various management practices on crop yield and soil properties under different environmental conditions. **Aims.** (1) We evaluated the Cropping System Model (CSM)-CERES-Maize and CSM-CROPGRO-Soybean model for NT and CT systems; and (2) compared the long-term impacts of NT and CT on crop yield and soil organic carbon (SOC). **Methods.** Two crop models, available in the Decision Support System for Agrotechnology Transfer (DSSAT), were calibrated and evaluated using maize (*Zea mays* L.) and soybean (*Glycine max* L.) yield data from 2006 through 2011 under CT and NT treatments. **Key results.** For crop yield, we showed that the coefficient of determination (R^2) for the calibration and evaluation phases of CERES-Maize model were 0.94 and 0.94, respectively, while the index of agreement (*d*) for these phases were 0.93 and 0.86. Similarly, the R^2 values for the calibration and evaluation phases of CROPGRO-Soybean model were 1.00 and 0.65, respectively, with *d*-values of 0.99 and 0.85. **Conclusions.** The results from these long-term (30-year) simulations suggest that compared to CT, the NT system enhanced SOC over time and, hence, crop yield and biomass production. **Implications.** Application of NT can be beneficial for enhancing the soils and crop production in the long-term as compared to the CT system.

Keywords: CERES-Maize, CROPGRO-Soybean, crop modelling, DSSAT, soil conservation, soil organic carbon, soil tillage, sustainability.

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Introduction

The Food and Agriculture Organization (FAO) has estimated that currently more than 820 million humans across the world face the problem of food shortage (FAOSTAT, https://www.fao.org/faostat/en/#data/FS). To address the growing demand for food, sustainable measures that aim to minimise the negative impacts of agricultural production on the environment need to be identified (Hobbs 2007). Traditionally, tillage has been a common practice used by producers across the world for planting crops. Tillage increases the decomposition of soil organic matter to provide nitrogen to plants, and also favours easier planting and weed control (Triplett and Dick 2008). However, the adverse effects of intensive tillage practices surfaced during the dust bowl of 1930s (Hobbs 2007). These adverse effects have been widely studied throughout the world under different environmental conditions (Barbera *et al.* 2012; Laudicina *et al.* 2015). Many researchers have found that tillage has a negative effect on the stability of the soil structure (Watts *et al.* 1996; Munkholm and Schjønning 2004), porosity (Schjønning *et al.* 2007; Eden *et al.* 2011), organic carbon, and making soils vulnerable to wind and water erosion. Heavy machinery used for tillage has led to soil compaction and degradation of the soil structure (Schjønning *et al.* 2012), and hence, a reduction in crop yield. Therefore, reducing the tillage operations could be a crucial management practice in sustaining soil health and improving crop yield.

Reducing tillage operations can enhance soil organic matter, microbial biomass and diversity (Laudicina *et al.* 2011; de Moraes Sá *et al.* 2015). Reducing tillage intensity, in general, enhances soil quality, C sequestering potential and lowers carbon losses (Álvaro-Fuentes *et al.* 2008; Barbera *et al.* 2012; Laudicina *et al.* 2014). Irrespective of the tillage practices, different cropping systems play an important role in improving soil organic carbon (SOC). A reduction in tillage intensity coupled with crop diversification enhances the C sequestration potential of the soil (Al-Kaisi *et al.* 2005) and reduces CO_2 emissions (Laudicina *et al.* 2014). Despite the fact that crop management without any tillage operations offers several advantages over tillage, mixed results have been observed during field studies. Several factors such as soil properties, weather and management practices influence crop yield and can have serious long-term repercussions on sustainability. Thus, careful selection of management operations can help achieving the desired goal for sustainability for crop yield and soil health in the upcoming decades.

Maintaining long-term field trials can be economically expensive and laborious, but with the advancement in technology, crop simulation models can help with addressing the complex problems of selecting management operations faced today. The Decision Support System for Agrotechnology Transfer (DSSAT) is a suite of crop simulation models that function on the plant–soil–atmosphere dynamics to predict crop, soil and hydrological outputs under various weather and soil conditions (Jones *et al.* 2003; Hoogenboom *et al.* 2019*a*). DSSAT can be used for estimating production, resource utilisation and risk assessment for various production systems (Jones *et al.* 1998; Tsuji *et al.* 1998). The Cropping Systems Model (CSM) of DSSAT has been used worldwide for a wide range of environmental conditions and crop management practices to simulate crop yield (Li *et al.* 2015; Adhikari *et al.* 2017; Singh *et al.* 2019). Although crop models that are used to simulate crop growth are powerful tools, a system approach requires an acute assessment of how management practices alter the soil processes over long periods of time (Bowen *et al.* 1998). The advantage of using DSSAT in crop modelling is the cropping sequence module, which enables the simulation of diverse crop rotations over long periods and aid in assessing site specific impacts of various management practices (Thornton *et al.* 1995; Singh *et al.* 1999*a*). For simulating soil organic matter and residue dynamics, DSSAT is equipped with the CERES-Godwin (Godwin and Singh 1998) and the CENTURY-Parton modules (Parton *et al.* 1988, 1994; Gijsman *et al.* 2002). The CERES-Godwin utilises the PAPRAN model, which was developed for small grains and pastures and does not recognise the residue layer formed on the soil surface (Seligman and van Keulen 1980). However, the CENTURY model recognises the residue layer and is more effective in simulating carbon, nitrogen, phosphorus, and sulfur under various production systems (Gijsman *et al.* 2002).

To simulate diverse crop rotations, predict future yield and evaluate alternate management operations, the crop simulation models first need to be evaluated for the specific site or region with measured data (Hunt and Boote 1998; Hoogenboom *et al.* 2012). Maize (*Zea mays* L.)–soybean (*Glycine max* L.) is the traditional crop rotation followed in South Dakota with more than 5 million ha for each crop being planted in 2018 (USDA-NASS 2018). Considering the advantages of no-tillage (NT) over conventional tillage (CT) with respect to crop yield and soil quality, the present study was conducted with the aim of addressing the following objectives to: (1) evaluate the performance of CSM-CERES-Maize and CSM-CROPGRO-Soybean modules by using the CENTURY-based soil organic matter module for simulating SOC under maize–soybean rotations; and (2) compare long-term simulated maize and soybean yield under conventional chisel plough and no-tillage management practices.

Materials and methods

Study site, treatments and long-term data

The experimental site was located at the Southeast Research Farm (SERF) of the South Dakota State University, Beresford, USA (43°02′58″N, 96°53′30″W). The experiment commenced in 1991 to study the effect of tillage operations and crop rotations on crop yield and soil properties. The soil at the experimental site was classified as Egan soil series (Fine-silty, mixed, super active, mesic Udic Haplustolls) (NRCS 2018). The plots were established on flat areas that have a slope of less than 1%. The experiment consisted of two tillage systems: (1) no-tillage (NT); and (2) conventional (chisel plough) tillage (CT) managed with a 2-year maize–soybean rotation. These study treatments were laid out in a randomised complete block design with four replications. Plots under CT were tilled with a chisel plough in the fall at a depth of approximately 20 cm, and in the spring a field cultivator was used up to a depth of approximately 10 cm. In the NT plots, crop residue for each crop was left on the soil surface after harvesting. In these treatments, the maize and soybean crops were planted during the summer at a row distance of 76 cm without removing any residue from the previous crop. The seeding rate for soybean was fixed at 400 000 seeds per hectare and was approximately 75 000 seeds per hectare for maize. The planting date for maize ranged from 23 April to 8 June, and for soybean ranged from 2 May to 21 June, depending upon the weather. For fertilisation, N and P were supplied to the maize crop depending upon the site-specific recommendations. The crops were mechanically harvested with a combine by making passes from the centre of the plot, and the data from the weigh wagon were used for crop yield estimation. The complete experimental setup has been described in detail by Alhameid et al. (2017). The weather data for the SERF for the period from 2003 to 2011 were obtained from the South Dakota State Mesonet Database (https://climate.sdstate.edu/).

DSSAT model

Model input

For simulating crop growth and yield for this study, the CSM-CERES-Maize and CSM-CROPGRO-Soybean models were used along with the CENTURY module for the soil organic matter in the DSSAT (ver. 4.7.2) (Hoogenboom et al. 2019b). As part of minimum dataset required for functioning of the simulation modules, the data on management operations, soil profile characteristics, daily weather and cultivar selection were entered into DSSAT (Hoogenboom et al. 2012). For crop management, the planting date, planting method, planting distribution, plant population, row spacing and planting depth were used separately for each crop, and a fallow period during the winter period was included as a part of the rotation. Similarly, there was a fallow period that started in the fall of 2003 followed by planting of a new crop in the spring of 2004.

For comparing the tillage operations in DSSAT, a tillage operation was performed using a chisel plough to a depth of 20 cm in the fall after crop harvest, and cultivator to a depth of 10 cm in the spring prior to planting for the CT treatment. In DSSAT, these operations were performed during the fallow period. For the NT, the tillage was not included for simulating the crop rotation. For both maize and soybean, only 10% of biomass under NT system was harvested and the remainder of the crop residue was carried forward to the next season. Further information on how crop residue is handled in DSSAT-Century module can be found in Gijsman et al. (2002). WeatherMan, a weather data utility programme of DSSAT (Pickering et al. 1994) was used to process all the weather data from 2003 to 2011 for this study. DSSAT requires daily minimum and maximum air temperature (°C), total precipitation (mm) and total solar radiation (MJ m^{-2}). Soils data required for DSSAT were obtained from the Natural Resources Conservation Service (NRCS) soil survey site (NRCS 2018). The soil profile data on basic soil physical and chemical characteristics is in Table 1.

Simulations for 9 years (2003–2011) were conducted in the DSSAT sequence analysis mode for a continuous simulation of the soil water and nutrient dynamics (Thornton et al. 1995; Bowen et al. 1998). Four management files (.SQX) were set up for the experiment, two with tillage and two without tillage. The rotation for both the files started with maize and soybean for the year 2003 and 2004, respectively (CS rotation), while for the other two files, the rotation started with soybean and maize in 2003 and 2004, respectively (SC rotation). The data on cropping sequence along with treatments are in Table 2. The focus of the study was to evaluate model performance for simulating crop yield. For the tillage treatments in DSSAT, the soil organic matter module increases the organic matter decomposition rate by 1.6 times than the NT and also redistributes the organic matter up to the tillage depth, while for the NT treatment the model treats the residue as a mulch layer (Porter et al. 2010).

Calibration and evaluation

The parameters for any model need to be adjusted so that an acceptable fit between the simulated and observed data is achieved. In DSSAT, the cultivar coefficients were estimated for calibration. These coefficients were further evaluated against the observed data to check their accuracy. The simulated growth stages for each crop are dependent on these coefficients and therefore, important to determine

Table 1. Soil water holding characteristics and root growth factor for each horizon used for simulating the long-term maize–soybean rotation at Beresford, South Dakota, USA (data extracted from NRCS 2018).

Depth (cm)	Lower limit of plant extractable soil water (cm^3 cm^{-3})	Drained upper limit (cm^3 cm^{-3})	Saturated soil water content (cm^3 cm^{-3})	Root growth factor (0–1)	Saturated hydraulic conductivity (cm h^{-1})
20	0.196	0.327	0.532	1	3.24
66	0.166	0.306	0.486	0.406	3.24
86	0.157	0.300	0.471	0.35	3.24
137	0.192	0.307	0.457	0.223	0.97
152	0.189	0.305	0.454	0.037	0.97

Depth (cm)	Bulk density (g cm^{-3})	Organic C (%)	Clay (%)	Silt (%)	Total nitrogen (%)	Cation exchange capacity (cmol kg^{-1})
20	1.12	2.610	27	62	0.23	18
66	1.28	0.754	25	63	0.20	12
86	1.33	0.290	25	63	0.17	12
137	1.37	0.290	25	44	0.11	12
152	1.38	0.174	25	44	0.11	12

Table 2. Chronological order of the crops grown, and the fallow period used for simulating the impacts of crop rotation on crop yield using DSSAT.

Year	CT-CS	NT-CS	CT-SC	NT-SC
2003	Maize	Maize	Soybean	Soybean
2004	Soybean	Soybean	Maize	Maize
2005	Maize	Maize	Soybean	Soybean
2006	Soybean	Soybean*	Maize	Maize
2007	Maize	Maize	Soybean*	Soybean*
2008	Soybean	Soybean	Maize	Maize
2009	Maize*	Maize*	Soybean	Soybean
2010	Soybean	Soybean	Maize	Maize
2011	Maize*	Maize*	Soybean	Soybean

Note: * represents the model calibration treatments.
CT, conventional tillage; NT, no tillage; CS, maize–soybean rotation; SC, soybean–maize rotation.

the cultivar coefficients prior to simulating final yield. The cultivar coefficients were determined with experimental data for the years that had minimum environment stress during maize and soybean production. Simulations were made from 2003 to 2011 and a subset of years 2006–2011 consisting of both treatments were used for model calibration and evaluation. The initial 3-year time period from 2003 to 2005 was used as a warm-up period for the model (Adhikari *et al.* 2017). Initially, crop growth parameters were estimated using the GLUE programme (He *et al.* 2010) of DSSAT (Hoogenboom *et al.* 2019*b*). However, the parameters were refined manually for the above-mentioned subset of years, when the entire crop rotation was simulated. The CERES-Maize model was calibrated for crop yield for 2009 and 2011 (n = 4), and evaluated for crop yield for 2006, 2007, 2008 and 2010 (n = 8). Similarly, the CROPGRO-Soybean model was calibrated for grain yield for 2006 and 2007 under NT and CT treatments (n = 3), while grain yield for 2008–2011 was used for evaluation of the model (n = 8).

Model application: long-term simulations

The initial simulations compared the crop yield for NT and CT treatments from 2003 to 2011. However, the calibrated model was used to simulate future crop production under NT and CT for a long-term period (30 years). The CT-CS and NT-CS rotations were compared using the built-in weather generator module WGEN (Richardson and Wright 1984), which is a part of the CSM model for simulating crop yield for 30 years (2003–2032) with 30 realisations to account for model uncertainty. The WGEN weather generator generated daily weather data, for the required time period using, by extracting climate parameters for the experimental using 15 years of historical weather data. The climate parameters from the historical weather data were calculated with the Weatherman utility programme (Pickering *et al.* 1994).

Statistical analysis

Since each estimated statistic has its own limitations for evaluation of model performance, a number of statistics were estimated so that a representative inference could be obtained (Yang *et al.* 2014). Simulated maize and soybean yields were compared with the observed yield to calculate coefficient of determination (R^2) (Legates and McCabe 1999), index of agreement (d) (Willmott 1982), percent relative root mean squared error (RRMSE, expressed as percentage of mean observed data) and mean error (E) (Addiscott and Whitmore 1987; Yang *et al.* 2000), calculated as:

$$R^2 = \left(\frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2} \sqrt{\sum (y_i - \bar{y})^2}} \right)^2$$

$$d = 1 - \frac{\sum (y_i - x_i)^2}{\sum (|y_i - \bar{x}| + |x_i - \bar{y}|)^2}$$

$$\text{RMSE} = \sqrt{\frac{\sum (y_i - x_i)^2}{n}}$$

$$\text{RRMSE} = \frac{\text{RMSE}}{\bar{x}} \times 100$$

$$E = \frac{\sum (y_i - x_i)}{n}$$

where n is the number of observations, y_i is the simulated data, x_i is the observed data, $\bar{y}$ is the mean of simulated data and $\bar{x}$ is the mean of observed data. For the current study, the coefficient of determination, $R^2 \geq 0.75$ was considered as good agreement; and $0.75 \geq R^2 \geq 0.50$ as the average. The index of agreement, $d \geq 0.90$ as excellent agreement between the model data and observed data; $0.9 \geq d \geq 0.8$ as good agreement and $0.80 \geq d \geq 0.70$ as moderate agreement between simulated and observed data (Liu *et al.* 2013). Due to the lack of any particular rule for inferring RRMSE, we considered RRMSE ≤ 15% as good fit, 15–30% as moderate and ≥30% as poor (Liu *et al.* 2013). The aim of the experiment was to maximise R^2 and d, while minimising RRMSE and E. The statistical analysis was conducted using the package hydroGOF (Zambrano-Bigiarini 2011) in RStudio ver. 1.1.453 (RStudio RsT 2015).

Results and discussion

Calibration and evaluation

The model calibration using grain yield was carried out for the minimum stress years of production for both maize and soybean. The calibration of CSM-CERES-Maize was conducted by adjusting five cultivar coefficients that govern the reproductive and vegetative stages of the crop. Similarly, the CSM-CROPGRO-Soybean model was calibrated by adjusting 12 cultivar coefficients. Cultivar coefficients governing crop development were adjusted prior to those governing crop yield. The calibrated coefficients, along with the default values are in Table 3. The changes in cultivar coefficients can also be attributed to diverse weather conditions across the years and change in planting dates.

The CSM-CERES-Maize model was calibrated using crop yield for 2009 and 2011. The simulated and observed data showed excellent agreement with $R^2 = 0.94$, $d = 0.93$, RRMSE = 12.2 % and $E = -384.3$. Also, the evaluation of CSM-CERES-Maize was conducted using yield data for 2006–2008 and 2010. Similar to the calibration results, the model evaluation depicted a good agreement between the simulated and observed maize yield with $R^2 = 0.94$, $d = 0.86$, RRMSE = 25.0% and $E = 1766.5$ (Table 4).

Likewise, the CSM-CROPGRO-Soybean model was calibrated using soybean yield under NT for 2006 and 2007, and CT treatment for 2007. A strong agreement was observed between the simulated and observed yield with $R^2 = 1.00$, $d = 0.99$, RRMSE = 1.3% and $E = 28.3$. The evaluation period for the CROPGRO-Soybean model was from 2008 to 2011, and data from the NT and CT treatments was used for this purpose. The statistical parameters depicted a good agreement for the evaluation period between the observed and simulated soybean yield with $R^2 = 0.65$, $d = 0.85$, RRMSE = 12.5% and $E = -183.1$ (Table 5). Similar results for simulating grain and biomass yield under different tillage scenarios have been observed in case of wheat (Rani *et al.* 2020).

Based on the calculated statistical parameters, it can be concluded that the CSM-CERES-Maize and CROPGRO-Soybean models can simulate crop yield under NT and CT for 2-year maize–soybean rotation. Despite a decent model performance, the variation between observed and simulated yield can be attributed to any stress induced by insect pest or disease. Moreover, weed pressure or nutrient competition by weeds was not considered during the simulations. Therefore, the model overpredicted the crop yield. The model predictions from the current study were similar to those of other simulation studies (Liu *et al.* 2013).

Simulations: 2006–2011

Simulated yield

For the calibration and evaluation period (2006–2011), the NT treatment performed slightly better than the CT with respect to crop yield. The average maize yield for the NT

Table 3. Estimated cultivar coefficients following calibration of the CSM-CERES-Maize and CSM-CROPGRO-Soybean models.

Cultivar coefficient		Coefficient value	
		Default	Calibrated
Maize			
P1:	Thermal time from emergence of seedling up to juvenile phase (degree days above base temperature of 8°C)	240.0	270.1
P2:	Extent of delay in development with unit hour increase in photoperiod (days)	0.7	0.7
P5:	Thermal time or degree days from silking to physiological maturity (degree days above base temperature of 8°C)	990.0	880
G2:	Maximum number of kernels per plant	907.0	805.4
G3:	Kernel filling rate (mg day^{-1})	8.80	9.17
PHINT:	Interval between two consecutive leaf tip appearance (degree days)	38.9	38.9
Soybean			
CSDL:	Critical short day length (h)	14.33	13.93
PPSEN:	Slope of the relative response of development to photoperiod with time (1/h)	0.110	0.18
EM-FL:	Time between plant emergence and flower appearance (photothermal days)	20.77	12.83
FL-SD:	Time between first flower and first seed (R5) (photothermal days)	11.70	11.58
SD-PM:	Time between first seed (R5) and physiological maturity (R7) (photothermal days)	35.2	31.5
LFMAX:	Maximum leaf photosynthesis rate (mg CO_2 m^{-2} s^{-1})	1.030	1.381
SLAVR:	Specific leaf area of cultivar under standard growth conditions (cm^2 g^{-1})	375.0	305.0
SIZLF:	Maximum size of full leaf (three leaflets) (cm^2)	180.0	140.1
WTPSD:	Maximum weight per seed (g)	0.19	0.17
SFDUR:	Seed filling duration for pod cohort at standard growth conditions (photothermal days)	23.0	17.2
SDPDV:	Average seed per pod under standard growing conditions (number/pod)	2.20	1.76
THRSH:	Threshing percentage	76.0	78

Table 4. Model calibration and evaluation statistics for simulated maize yield under conventional-till (CT) and no-till (NT) system using CSM-CERES-Maize.

	Year	Treatment	Observed yield (kg ha^{-1})	Simulated yield (kg ha^{-1})	R^2	*d*	RMSE (%)	*E*
Calibration (*n* = 4)	2009	CT	12 364	12 847	0.94	0.93	12.2	−384.3
	2009	NT	11 978	12 676				
	2011	CT	8422	6083				
	2011	NT	8411	8032				
Evaluation (*n* = 8)	2006	CT	6305	5868	0.94	0.86	25.0	1766.5
	2006	NT	4631	5198				
	2007	CT	7196	9055				
	2007	NT	7196	9296				
	2008	CT	9284	11 551				
	2008	NT	9408	12 412				
	2010	CT	11 552	13 538				
	2010	NT	10 628	13 414				

Table 5. Model calibration and evaluation statistics for simulated soybean yields under conventional-till (CT) and no-till (NT) system using CSM-CROPGRO-Soybean.

	Year	Treatment	Observed yield (kg ha^{-1})	Simulated yield (kg ha^{-1})	R^2	*d*	RMSE (%)	*E*
Calibration (*n* = 3)	2006	NT	2784	2785	1.00	0.99	1.3	28.3
	2007	CT	3012	3031				
	2007	NT	3150	3215				
Evaluation (*n* = 8)	2008	CT	3006	2912	0.65	0.85	12.5	−183.1
	2008	NT	3072	3193				
	2009	CT	3384	2865				
	2009	NT	3600	2759				
	2010	CT	3312	3199				
	2010	NT	3438	3198				
	2011	CT	2070	2051				
	2011	NT	2160	2400				

treatment was 10 171 kg ha^{-1}, ranging from 5198 kg ha^{-1} to 13 414 kg ha^{-1}, whereas, the average maize yield under CT over the years was 9823 kg ha^{-1}, ranging from 5868 kg ha^{-1} to 13 538 kg ha^{-1} (Table 4). For soybean under NT, the mean simulated yield was 2925 kg ha^{-1} with a minimum of 2759 kg ha^{-1} and a maximum of 3215 kg ha^{-1}; whereas the mean soybean yield for CT was 2625 kg ha^{-1}, ranging from 1693 kg ha^{-1} to 3199 kg ha^{-1} (Table 5). The simulated crop yield values were almost similar for the first year of simulations; i.e. 2003 for both CT and NT systems, as they remained unaffected by one cycle of tillage. Most of the soil characteristics take a long time to change according to the management practices, which could be attributed as one of the reasons for no difference between the two tillage treatments during the initial years. Simulated yield for most of the remaining years was higher under NT as compared to the CT. Also, tillage has a transient effect during the simulations (Porter *et al.* 2010). Therefore, small cumulative changes during the tillage operations may require simulations over a longer period than the duration of this study.

Simulated yield for maize was slightly higher than the observed for most of the evaluation years for both the tillage treatments, and the RRMSE for the evaluation period remained as 25%. The variation in simulated yield for soybean was lower as compared to the maize. Simulated yield was higher in 2009 for the CT and NT treatments. However, the RRMSE for the evaluation period remained fair at 12.5%. Considering the RRMSE for the evaluation periods, the simulated yield provided a good fit against the observed yield and hence, the evaluation showed that the CSM-CROPGRO-Soybean and CSM-CERES-Maize can be used for the simulation of maize–soybean cropping systems.

Simulated SOC

The major effect of tillage practices could be observed in the SOC. The tillage practice during the fall was applied up to a depth 20 cm using the chisel plough and up to a depth of 10 cm during spring prior to planting. As part of simulating the soil organic matter balance, the CENTURY module considers the residue layer that was left on the soil surface for the NT treatment. However, for the CT treatment, this residue or mulch layer was being incorporated up to the depth of tillage. The initial SOC stock in top layer (0–20 cm) for all the four treatments was similar at 58 390 kg ha^{-1}. Therefore, any changes in the organic carbon can be attributed to the changes in management or tillage treatments. While comparing the two tillage treatments, SOC was higher for the NT irrespective of the rotation (Fig. 1). A sharp decline in the SOC can be observed immediately following the fall tillage treatment, whereas SOC remained almost constant for the NT treatment. Maize residue contributed more to the SOC than the soybean because of the higher biomass production. Hence, SOC up to 20 cm soil depth was found higher in CS rotation than the SC rotation because the CS rotation included five crops of maize from 2006 to 2011, whereas the SC rotation included four crops of maize. In the DSSAT simulations, tillage boosts the soil organic matter decomposition rate temporarily for 30 days following tillage (Gijsman *et al.* 2002; Porter *et al.* 2010). In addition, the organic matter left on the surface had a lower decomposition rate when tillage was not practiced. This aided in the slow build-up of SOC due to a lower mineralisation rate. The NT practice has been reported to increase SOC up to 30% as compared to the CT (Kennedy and Schillinger 2006). The simulated results depicted an increase in SOC under NT and are in accordance with the field experiments conducted to study the impact of tillage on SOC (Alhameid *et al.* 2017).

Simulated extractable water

NT has been for a majority of cases approved as a better management practice for conserving soil moisture than conventional tillage. Several studies have reported an improved infiltration rate and hydraulic conductivity under a NT as compared to a CT practice (Kahlon *et al.* 2013). Higher SOC, higher porosity and lower bulk density can be the possible reasons for higher infiltration under NT compared to that under CT. Higher infiltration under NT can be inferred as higher soil moisture being extracted by crops under this system as compared to the CT (Fig. 2). The initial extractable (plant available) water at the onset of simulation date for all the treatments was 195 mm. Since all four treatments received the same amount of precipitation, the extractable water for NT was higher than for the CT treatment, irrespective of the rotation. The cause for the larger amount of plant available water could be the residue layer formed on the surface in the NT treatment. The surface residue layer decreased the runoff and increased the surface storage capacity. Higher organic matter as a result of NT also aided in increasing the water holding capacity of the soil (Porter *et al.* 2010). The residue layer hindered the direct sunlight and reduced the soil evaporation losses resulting in more water being infiltrated into the soil profile. Therefore, during the growing season, the NT treatment, which had crop residue acting as mulch layer, had lower soil evaporation as well when compared to the CT (Lal *et al.* 2007). Thus, NT reduced evaporation losses and helped in increasing plant available water (Lamm *et al.* 2009).

Simulated N fixation and N uptake

Simulating the amount of N fixed during the soybean phase of the rotation can be considered important to the sustainability of the rotation. The NT management promoted N fixation compared to the CT, which can also be inferred from the simulated data (Fig. 3*a*). The soil profile remained undisturbed in the NT management as compared to the CT and favoured higher N fixation by the microbial community (Okoth *et al.* 2014). From 2006 to 2011, nitrogen fixation by soybean under NT varied from 151 kg ha^{-1} to 217 kg ha^{-1}, whereas it ranged from 129 kg ha^{-1} to 210 kg ha^{-1} under CT treatment. In addition, nitrogen uptake during the maize and soybean phases was higher for NT than for the CT. Average nitrogen uptake for maize under NT (2006–2011) was found to be 256 kg ha^{-1} ranging from 234 kg ha^{-1} to 283 kg ha^{-1}, while the mean nitrogen uptake for maize under CT was 254 kg ha^{-1} ranging from 236 kg ha^{-1} to 288 kg ha^{-1}. Similarly, nitrogen uptake by soybean (2006–2011) averaged 79 kg ha^{-1} varying from 49 kg ha^{-1} to 133 kg ha^{-1} under NT treatment. For the CT treatment, mean nitrogen uptake by soybean was estimated to be 74 kg N ha^{-1}, with a minimum of 46 kg N ha^{-1} and maximum of 115 kg ha^{-1}. The simulation time for calibration and evaluation period might be insufficient; thus, it would be worthwhile to observe N uptake for a longer simulation period (Fig. 3*b* and *c*).

Model application: sequential cropping systems

Long-term simulations

The weather generator WGEN allows for the generation of daily weather data that represent the local climatology of the study site. These generated weather datasets can be used to assess long-term trends in crop production with respect to management practices. The climate parameters for the study site were estimated using 15 years of historical daily weather data (Soltani and Hoogenboom 2003). To obtain a fair estimate of the performance and associated uncertainty to weather variability of the two management practices over long-term, the simulations were conducted with 30 replications of generated weather data.

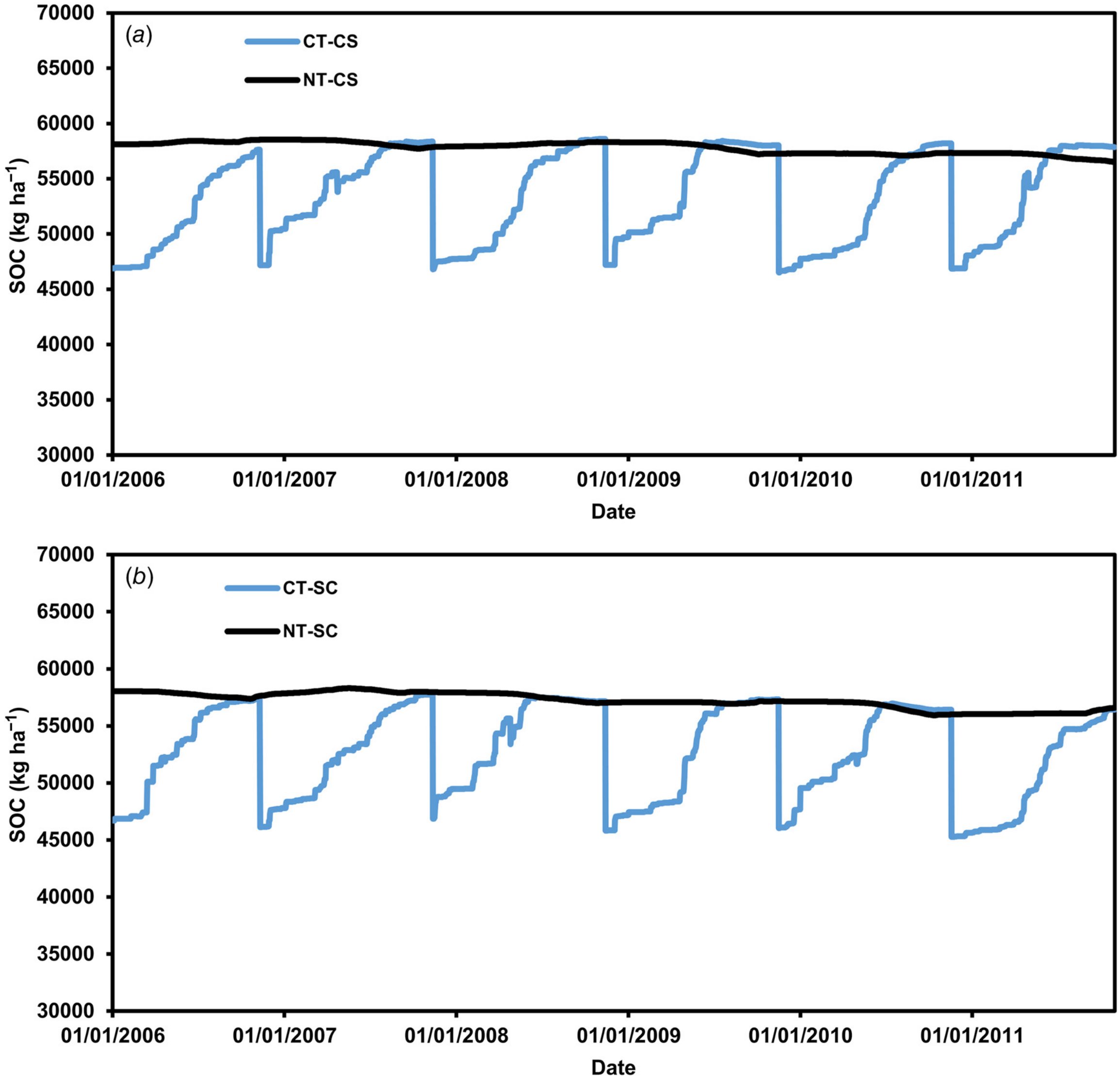

Fig. 1. Simulated soil organic carbon (SOC, kg ha^{-1}) using the CENTURY module of DSSAT for the NT and CT treatments from 2006 to 2011. NT, no tillage; CT, conventional tillage; CS, maize soybean rotation; SC, soybean maize rotation.

Crop yield

Simulated crop yield based on the generated weather data indicated a slight benefit for the NT over the CT. Maize and soybean crops reportedly performed better under NT treatment for 30 years (hypothetical years 2003–2032; Fig. 4). The average maize yield under NT for 30 years was 8309 kg ha^{-1} (22% gain over CT) ranging from 7078 kg ha^{-1} to 9258 kg ha^{-1}, while under CT, the average maize yield was 6809 kg ha^{-1} ranging from 5343 kg ha^{-1} to 8204 kg ha^{-1}. The average soybean yield under NT was 2517 kg ha^{-1} (24% gain over CT) ranging from 2278 kg ha^{-1} to 2803 kg ha^{-1}. In case of CT, the average soybean yield was 2032 kg ha^{-1} with minimum reported at 1657 kg ha^{-1} and maximum of 2281 kg ha^{-1}. The NT performed better than CT for all years. A similar increase in yield of maize has been reported in China where maize yield was 1.4% higher under NT as compared to the CT (He *et al.* 2011). Studying the economic aspects of CT and NT production systems may help with reaching a better decision on deciding when to adopt a system.

A number of possible reasons could be attributed for the enhanced yield for the NT production system. Most of the NT advantages discussed during the calibration and evaluation phase followed a trend for the long-term simulations. These small cumulative effects could have resulted in yield improvements and biomass production under NT. A glance at the seasonal runoff for 30 years indicated that the average simulated seasonal runoff under the NT system was

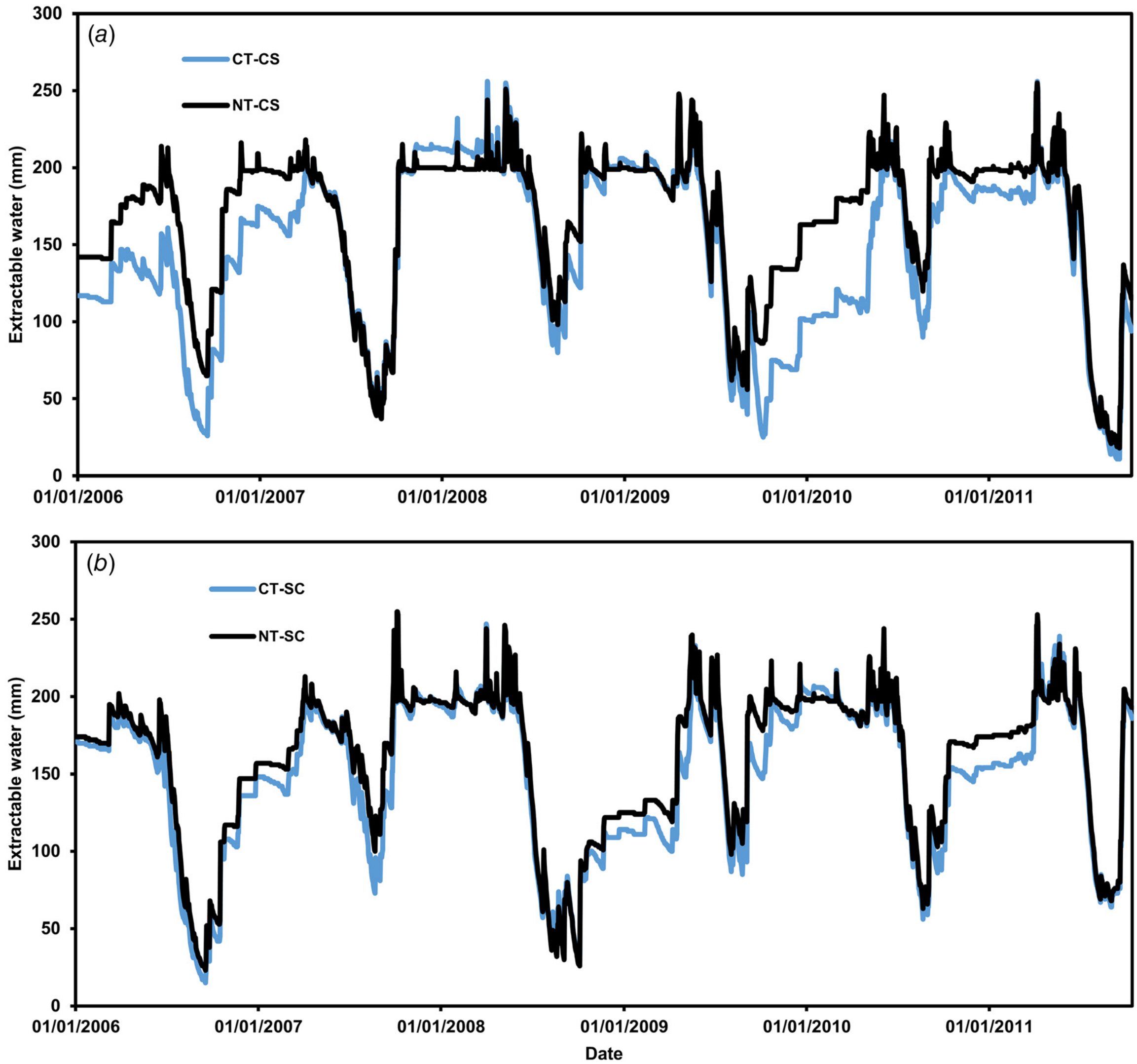

Fig. 2. Simulated extractable water (mm) under NT and CT treatments from 2006 to 2011. NT, no tillage; CT, conventional tillage; CS, maize soybean rotation; SC, soybean maize rotation.

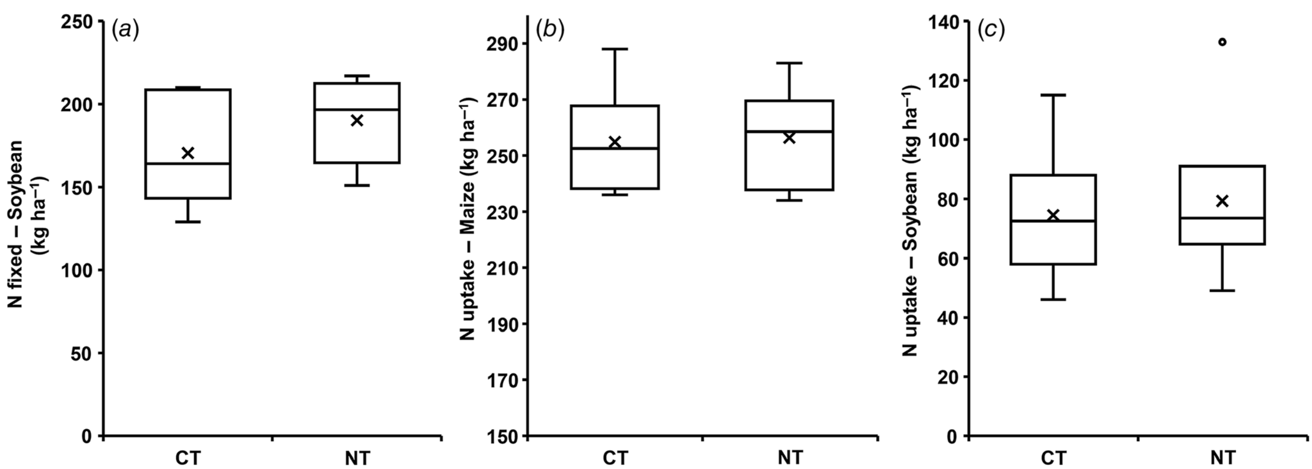

Fig. 3. Simulated seasonal nitrogen components (2006–2011) including (*a*) quantity of nitrogen fixed (kg ha^{-1}) during soybean phase, (*b*) N uptake by maize and (*c*) N uptake by soybean under CT and NT crop rotation from 2006 to 2011.

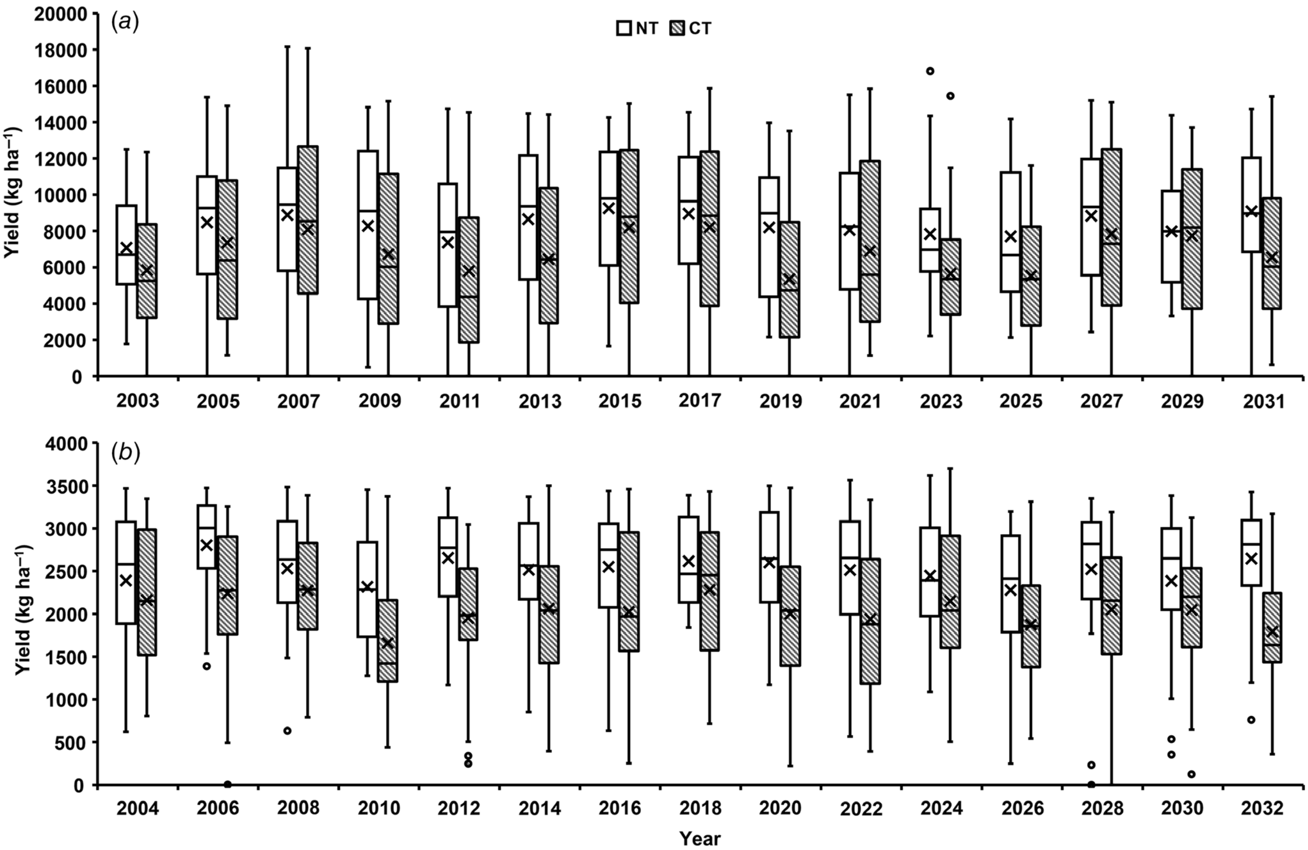

Fig. 4. Simulated (*a*) maize and (*b*) soybean yield (kg ha^{-1}) based on 30 years of generated weather data using WGEN; conventional tillage (CT) vs no-till (NT) (2003–2032).

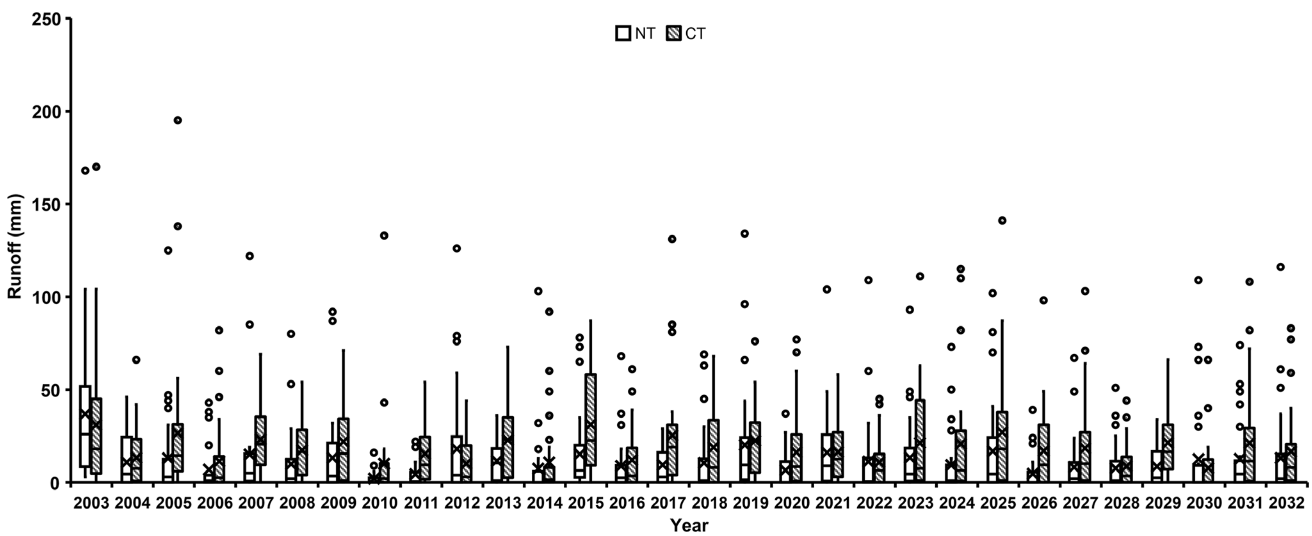

Fig. 5. Simulated seasonal runoff (mm) based on 30 years of generated weather data using WGEN; conventional tillage (CT) vs no-till (NT) (2003–2032).

11.8 mm ranging from 2.1 to 36.9 mm, and while under CT system it was 18.2 mm ranging from 7.7 to 31.2 mm (Fig. 5). Lower surface runoff suggested that smaller amount of precipitation was lost towards the surface runoff (Singh *et al.* 1999*b*). The seasonal runoff was higher for NT as compared to CT for only the first year of the simulation.

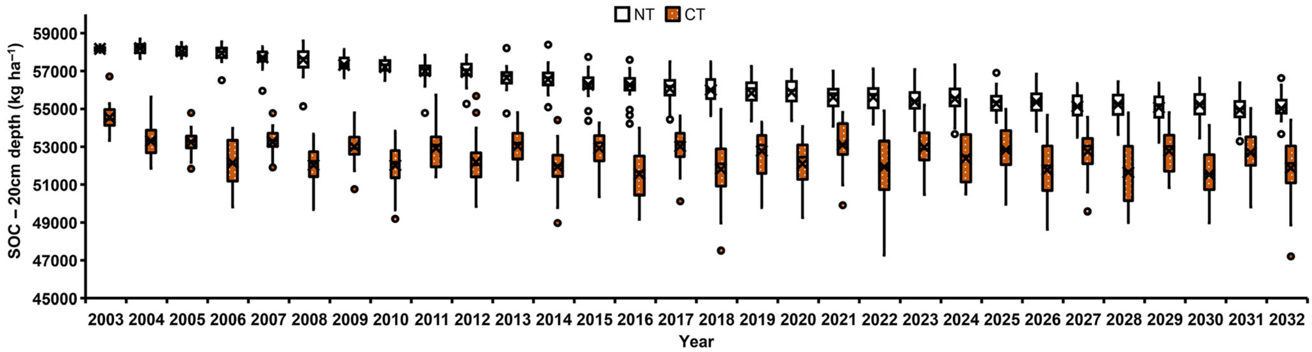

Fig. 6. Simulated soil organic carbon (kg ha^{-1}) based on 30 years of generated weather data using WGEN; conventional tillage (CT) vs no-till (NT) (2003–2032).

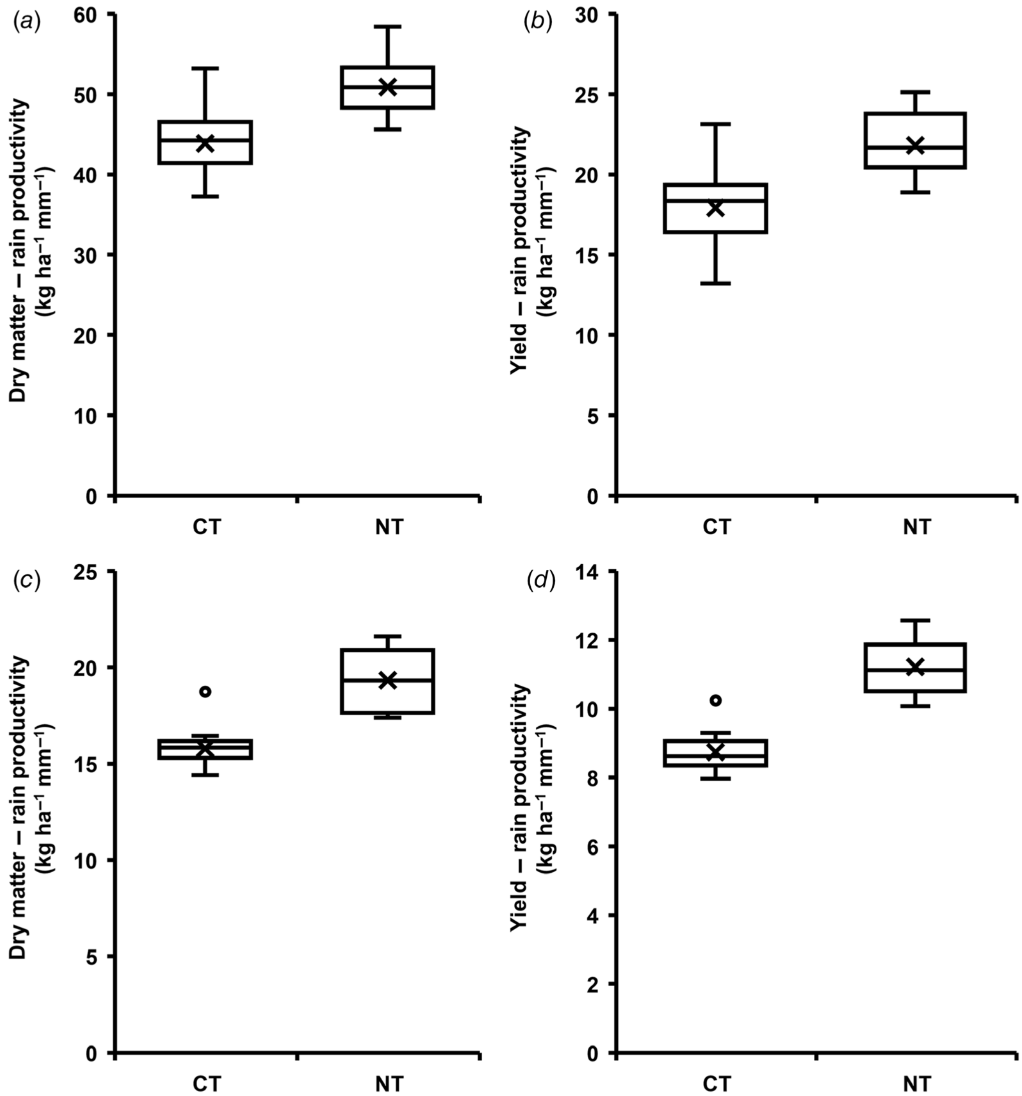

Fig. 7. Average simulated dry matter–rain and yield–rain productivity (kg ha^{-1} mm^{-1}) for maize (*a*, *b*) and soybean (*c*, *d*) respectively, based on 30 years of generated weather data using WGEN; conventional tillage (CT) vs no-till (NT).

Soil organic carbon

As discussed during the calibration and evaluation phases, the SOC up to 20 cm depth was higher in NT compared to the CT. Similar trends were observed in the long-term simulations. The SOC for the 20 cm depth was averaged over 30 realisations and the variation between the two treatments depicted for SOC could be considered significant (Fig. 6). This suggests that SOC was enhanced through NT management of residue. The lower decomposition rate of soil organic matter indeed helped build up the SOC. The gap between the SOC for the two treatments appears to be larger in the initial years, which could have been due to the lack of a spin-up period required for carbon pools to reach equilibrium, but overall the trend stayed consistent. Higher SOC in the soil leads to higher soil aggregate stability, which makes the soil less vulnerable to any kind of erosion. No-till practices have been found to increase soil aggregate stability as compared to CT (Mikha and Rice 2004).

Crop performance

The maize–soybean production discussed above uses precipitation as a source for soil moisture without any supplemental irrigation. The physiological aspects of maize and soybean production under NT system are therefore the important components that can help in decision making when comparing the two contrasting production systems. The relationship between precipitation and yield or dry matter production for both maize and soybean are in Fig. 7. The average yield and dry matter produced per unit of rainfall for maize under NT were 21.8 and 50.9 kg ha^{-1}, respectively, as compared to 17.9 and 43.9 kg ha^{-1} under CT, respectively. The average yield and dry matter production per unit rainfall for soybean under NT were 11.2 and 19.3 kg ha^{-1}, respectively; and under CT, these values were 8.7 and 15.8 kg ha^{-1}, respectively. This relation can also be explained by the fact that evapotranspiration losses were lower under NT as discussed previously. As a result, yield or dry matter production per unit evapotranspiration (kg ha^{-1} mm^{-1}) for maize and soybean was higher under NT as compared to the CT (Fig. 7). The average maize yield and dry matter production per unit ET under NT were 19.9 and 45.8 kg ha^{-1} mm^{-1}, respectively, as compared to 15.8 and 38.2 kg ha^{-1} mm^{-1} under CT. Similarly, for soybean, the average yield and dry matter production per unit ET under NT were 11.8 and 20.0 kg ha^{-1} mm^{-1}, respectively, as compared to 7.7 and 13.8 kg ha^{-1} mm^{-1} under CT, respectively.

Conclusions

DSSAT performed fairly well in predicting the long-term crop yield for a 2-year maize–soybean rotation under NT and CT management practices. Maize and soybean yield were higher for NT as compared to the CT. Also, NT management improved N uptake by crops along with N fixation as compared to the CT. The long-term simulations indicated that NT was better with respect to crop productivity and SOC build up. Overall, the crop yield data collected at the Southeast Research Farm of the South Dakota State University proved to be beneficial in evaluating the CSM-CERES-Maize and CSM-CROPGRO-Soybean for the most prevalent crop rotation in the eastern South Dakota, and DSSAT model holds enormous potential in modelling crop growth and yield. The present simulation study suggests that application of NT can be beneficial for enhancing the soils and crop production in the long-term as compared to the conventional-till system.

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Data availability. The data that support this study will be shared upon request by the corresponding author.

Conflicts of interest. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Author contributions. TR performed the modelling simulations and prepared the manuscript with inputs from GH and SK. GH, SK and TN developed the concept, and reviewed the manuscript. PS provided the data required for simulation and reviewed the manuscript.

Author affiliations

[A]Department of Crop Sciences, University of Illinois, Urbana-Champaign, Champaign, IL, USA.

[B]Department of Agronomy, Horticulture and Plant Science, South Dakota State University, Brookings, SD, USA.

[C]Department of Agricultural and Biological Engineering, University of Florida, Gainesville, FL, USA.