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ORIGINAL ARTICLE

Using the DSSAT-CERES-Maize model to simulate crop yield and nitrogen cycling in fields under long-term continuous maize production

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Abstract Simulation models, such as the DSSAT (Decision Support System for Agrotechnology Transfer) Crop System Models are often used to characterize, develop and assess field crop production practices. In this study, one of the DSSAT Cropping System Model, CERES-Maize, was employed to characterize maize (*Zea mays*) yield and nitrogen dynamics in a 50-year maize production study at Woodslee, Ontario, Canada (42°13′N, 82°44′W). The treatments selected for this study included continuous corn/maize with fertilization (CC-F) and continuous corn/maize without fertilization (CC-NF) treatments. Sequential model simulations of long-term maize yield (1959–2008), near-surface (0–30 cm) soil mineral nitrogen (N) content (2000), and soil nitrate loss (1998–2000) were compared to measured values. The model did not provide accurate predictions of annual maize yields, but the overall agreement was as good as other researchers have obtained. In the CC-F treatment, near-surface soil mineral N and cumulative soil nitrate loss were simulated by the model reasonably well, with n-RMSE = 62 and 29%, respectively. In the CC-NF treatment, however, the model consistently overestimated soil nitrate loss. These outcomes can be used to improve our understanding of the long-term effects of fertilizer management practices on maize yield and soil properties in improved and degraded soils.

Keywords DSSAT · Cropping system model · CSM-CERES-Maize · Sequential simulation · Long-term experiment · Maize yield · Nitrate loss

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Introduction

Long-term experiments are crucial for determining fundamental crop, soil and ecological processes and their impacts on the environment (Johnston 1997;

Körschens 2006; Leigh and Johnston 1994; Mitchell et al. 2008; Payne 2006; Poulton 1995; Rasmussen et al. 1998; Zhao et al. 2010). Long-term experiments have shown, for example, that commonly used irrigation and nitrogen fertilization practices can produce substantial N leaching out of the root zone, which in turn results in environmental degradation and substantial economic loss to the producer (Edmeades 2003; Johnston 1997). Hence, long-term experiments are particularly useful for developing beneficial management practices (BMPs) which produce economically viable crop yields while maintaining soil quality and environmental health at acceptable levels.

Classical statistics, such as analysis of variance and regression, were the most frequently used methods in analysing long term experimental field data; and Barnett (1994) illustrated how they were used to analyze the long-term field data from Rothamsted, England. Payne (2006) concluded that since regression methods (i.e., Fisher's 5th-order Legendre polynomial, or multiple regression models between yield and climate data) could explain only about 10–40% of the variation in crop yield, many additional crop, soil and weather factors need to be included.

In recent decades, the use of long term field data to develop and evaluate dynamic simulation models make these data extremely valuable (Jenkinson et al. 1994; Körschens 2006; Leigh et al. 1994). The simulation models in turn reveal data gaps and errors, and thereby promote improved data collection and documentation (Hunt et al. 2001). In addition, dynamic crop and soil models facilitate detailed and systematic analyses by providing inexpensive, rapid and detailed estimations of crop growth and soil nutrient-water movement. By analysing model predictions, economic and environmental benefits can be compared among different crop production and soil management scenarios. After successful calibration and evaluation, a simulation model can be usefully applied to both the development of BMPs, and the analysis and forecasting of crop production systems (Jones et al. 2003; Saseendran et al. 2007).

Integrating long-term experimental data with model simulation is one of the objectives in the inter-linked group of submodels known as the DSSAT (Decision Support System for Agrotechnology Transfer) Crop System Model (Jones et al. 2003), and it has been successfully employed in long-term fertilizer, irrigation, pest management, and site-specific farming applications (Cabrera et al. 2007; Jones et al. 2003; Lobell and Ortiz-Monasterio 2006). Other models have also been used to simulate long-term experiments; e.g. the integrated Root Zone Water Quality Model (RZWQM) was used to simulate long-term management effects on crop production, tile drainage and water quality (Ahmed et al. 2007; Ma et al. 2007; Saseendran et al. 2007); the Agricultural Production Systems Simulator (APSIM) model was applied to simulate long-term cropping system with climate variability and irrigation management (Keating et al. 2003; Wang et al. 2008, 2009); the Environmental Policy Integrated Climate (EPIC) model was used to estimate crop growth, soil erosion, and nutrient loss by runoff and leaching (Izaurralde et al. 2006; Roloff et al. 1998; Williams 1995), and agroecological changes of 93-year farming transformation (Bernardos et al. 2001); and the integrated soil-crop HERMES model, was used to simulate 25 years of crop rotations on a long-term field experiment at Swift Current in south-western Saskatchewan, Canada (Kersebaum et al. 2008). A particularly useful feature of the DSSAT Crop System Model is its ability to handle site-specific crops and rotations (Bowen et al. 1998). Furthermore, incorporation of the CERES submodel into DSSAT allows simulation of soil carbon and nitrogen cycling in low-input systems, and the ability to simulate the effects of climate change on carbon sequestration and long term yield forecasting (Gijsman et al. 2002; Koo et al. 2007; Porter et al. 2009).

Maize (*Zea mays*) is the main field crop grown in southern Ontario, Canada, but yields vary substantially from year to year due to weather variations (Ahmed et al. 2007; Cabas et al. 2010; Drury and Tan 1995; Tan and Reynolds 2003), changes in cultivars and adoption of soil and crop management practices. Detailed characterization of the combined effects of weather, cultivars and field management on long-term maize yield and soil N dynamics are needed for the development of effective and region-specific BMPs for sustainable maize production. However, there are few simulations of long-term maize production in Canada and southern Ontario, in particular. Hence, a DSSAT-CERES-Maize simulation of a long-term continuous maize production experiment at Woodslee, Ontario was conducted. The field experiment was started in 1959 to study the long-term effects of fertilization, crop rotation and weather on crop yield (Drury and Tan 1995) and soil and water quality (Tan et al. 2002). The objectives of the study were to: (1) use the DSSAT-CERES-Maize model to simulate maize yield and soil nitrogen and water dynamics over 50 years of continuous maize production with and without fertilizer application; and (2) evaluate the DSSAT-CERES-Maize model by comparing simulated and measured maize yield and soil N data.

Materials and methods

Field experimental data

The data were collected from a 50 year long term experiment established in 1959 at the Honourable Eugene F. Whelan Experimental Farm, Agricultural and Agri-Food Canada, Woodslee, Ontario (42°13′N, 82°44′W, Elevation 186 m). The soil is Brookston clay loam (Orthic Humic Gleysol), which is a poorly drained, lacustrine soil with an average root zone texture of 28% sand, 35% silt, 37% clay, and an average pH of 6.1. Average organic carbon in the top layer (i.e., Ap horizon) was 2.0–2.5% and surface slopes are generally <0.1%. The cropping treatments included continuous maize versus a maize-oats-alfalfa-alfalfa rotation, and the fertilization treatments included no fertilization versus chemical fertilization. The fertilization treatments included both a pre-plant application of starter fertilizer as well as a sidedress application for maize at the 6 leaf stage. The starter fertilizer (16.8 kg N ha^{-1}, 67.2 kg P_2O_5 ha^{-1} and 33.6 kg K_2O ha^{-1}) was applied as a broadcast—incorporated application to the soil 1 day before planting (Table 1). The side-dress application was a band application (2–5 cm deep) of 112 kg N ha^{-1} 15 cm from either side of the maize when the maize was at the 6 leaf stage (Table 1). The no–fertilizer treatment did not receive any chemical or organic fertilizer over the 50 year period; and as a result, many of its soil physical and hydraulic properties (e.g. bulk density, hydraulic conductivity, organic carbon, etc.) were substantially degraded relative to the chemical fertilization treatment (Table 3). The history and treatments of the site were described previously (Bolton et al. 1970; Drury et al. 1998; Drury and Tan 1995; Tan et al. 2002). Two treatments were selected for this study, continuous corn/maize with fertilization (CC-F) and continuous corn/maize without fertilization (CC-NF). Each plot was 76.2 m long by 12.2 m wide, and tillage consisted of fall mouldboard ploughing to 0.15 m depth, then discing and harrowing in the spring prior planting. Herbicides were applied to both CC-F and CC-NF as required to control weeds.

Planting density varied from 37,000 to 50,000 seeds ha^{-1} from 1959 to 1982 and 55,000 seeds ha^{-1} from 1983 to 1996 with a 1.0 m row spacing (Drury and Tan 1995; Gregorich et al. 2001), and it was increased to 62,000 seeds ha^{-1} from 1997 to 2007 with a 1.0 m row spacing. In 2008, the density was increased to 75,000 seeds ha^{-1} with a row spacing of 0.76 m, which is a typical corn row spacing. Maize grain yields were measured annually in the fall by harvesting 33 m lengths of 10 interior rows, and then grain sub-samples were taken to determine grain moisture. Grain yields were normalized to 15.5% grain moisture content, and maize dry yield was also calculated. Each year after harvest, maize residues were incorporated into the soil by mouldboard ploughing. Soil nitrate leaching through drainage tiles was measured during 1998–2000 (Tan et al. 2002) and soil mineral N in the 0–15 and 15–30 cm layers were measured in 2008.

Model input/output and evaluation data

Model description

The Cropping System Model (CSM) of DSSAT is a well developed process-oriented model which is capable of simulating long term rotation experiments (Tsuji et al. 1994; Jones et al. 2003). Each crop in the rotation has a separate module to simulate phenology, daily growth, development and partition biomass to leaves, stems, roots, ears and grain based on the supply and demands of soil water, carbon and nitrogen and phosphorus nutrients in response to weather and management conditions (Jones et al. 2003). The current version of DSSAT (4.5) contains 10 separate models in the DSSAT-CSM to simulate the growth of 29 different crops as well as fallow fields (Daroub et al. 2003; Hoogenboom et al. 1999; Jones et al. 2003; Jones et al. 2001; Tsuji et al. 1994). There were two soil organic nitrogen submodels in

Table 1 Field management data from 1959 to 2008 for the continuous corn with fertilization (CC-F) treatment at Woodslee, Ontario, Canada

Year	Planting[a] (date)	Plant density (plant m^{-2})	Fertilizer application		Tillage application	
			Starter[b] (date)	Side-dress[c] (date)	Spring (date)	Fall (date)
1959–1965	May 10	5.0	May 5	Jun 19	May 11	Nov 10
1966–1982	May 10	5.4	May 5	Jun 19	May 11	Nov 10
1983	Jun 15	5.5	Jun 15	Jul 14	Jun 15	Nov 9
1984	Jun 6	5.5	May 5	Jun 28	May 5	Nov 1
1985	May 8	5.5	Apr 19	Jun 24	Apr 19	Nov 6
1986	May 15	5.5	Apr 14	Jun 26	Apr 14	Nov 13
1987	May 6	5.5	Apr 28	Jun 8	Apr 28	Nov 16
1988	May 12	5.5	Apr 29	Jun 16	Apr 29	Oct 31
1989	May 26	5.5	May 10	Jun 26	May 10	Nov 1
1990	May 3	5.5	May 1	Jun 18	May 1	Nov 1
1991	May 10	5.5	Apr 30	Jun 14	Apr 30	Oct 23
1992	May 12	5.5	May 5	Jun 30	May 5	Oct 29
1993	May 20	5.5	May 14	Jun 18	May 14	Oct 20
1994	May 10	5.5	May 4	Jun 17	May 4	Oct 24
1995	May 16	5.5	May 8	Jun 16	May 8	Oct 30
1996	May 30	5.5	May 27	Jun 27	May 27	Nov 6
1997	Apr 30	6.2	Jun 10	Jul 2	Jun 10	Nov 10
1998	May 19	6.2	May 19	Jun 19	May 19	Nov 17
1999	May 2	6.2	May 4	Jun 8	May 4	Nov 29
2000	Jun 21	6.2	Apr 17	Jul 12	Apr 17	Dec 5
2001	May 7	6.2	May 4	Jun 13	May 4	Nov 21
2002	May 28	6.2	May 5	Jun 27	May 5	Nov 13
2003	Jun 18	6.2	Apr 30	Jul 3	Apr 30	Dec 8
2004	Jun 8	6.2	Apr 29	Jul 8	Apr 29	Nov 22
2005	May 11	6.2	May 10	Jun 14	May 10	Nov 28
2006	May 30	6.2	Apr 28	Jun 29	Apr 28	Nov 28
2007	May 8	6.2	May 8	Jun 12	May 8	Nov 14
2008	May 6	7.5	Apr 24	Jun 17	Apr 24	Oct 20

[a] Both the continuous corn with fertilization (CC-F) and the continuous corn with no fertilization (CC-NF) treatments were planted on the same date, with the same plant density and tilled on the same dates

[b] Starter fertilizer were applied on the same rates of 16.8 kg N ha^{-1}, 67.2 kg P_2O_5 ha^{-1} and 33.6 kg K_2O ha^{-1} each year from 1959 to 2008

[c] Side-dress N fertilizer was applied on the same rate of 112 kg N ha^{-1} each year from 1959 to 2008

DSSAT 4.5: the CERES soil model and the Century soil model. For long-term sequence simulations, the Century-based soil model seems to predict soil organic nutrient processes and organic carbon dynamics more realistically than the CERES-based model (Gijsman et al. 2002), and hence the Century-based soil model was selected for this study. Porter et al. (2009) describe the organic carbon and carbon-mediated soil processes in the Century-based soil model. Since the crop in this study was continuous maize, the Maize submodel in DSSAT was selected.

Model input parameters

The required model inputs describe field management, daily weather, soil profile characteristics, initial soil condition, and cultivar characteristics. The primary field management inputs include crop planting date and density; fertilization rate, date and depth; tillage and irrigation systems; and the amount and method of residue incorporation. These data were assembled from publications (Drury and Tan 1995; Tan et al. 2002) and unpublished field notes, and they cover the period from 1959 to 2008. The key model inputs are summarized in Table 1.

The minimum weather input required to run DSSAT, includes daily solar radiation (MJ m^{-2}), daily maximum and minimum temperature (°C), and daily precipitation (mm). To meet this requirement, it was necessary to use daily weather data from both the Woodslee weather station adjacent to the field site, and the Harrow weather station which is 30 km from the field site (42°02′N, 82°54′W). For 1959–1977, Harrow weather data were used, and for 1978–2008, Woodslee weather data were used, except the solar radiation for 1978–1987 which was calculated using Harrow daily sun hour data. The *WeatherMan* tool (Pickering et al. 1994; Wilkens 2004) in DSSAT 4.5 was used to check data, estimate missing values and calculate solar radiation from sun hours. Monthly weather data for selected years was used for cultivar calibration (Table 2).

The soil profile input data included lower soil water limit or wilting point water content (cm^3 cm^{-3}), upper drainage limit or field capacity water content (cm^3 cm^{-3}), upper soil water limit or saturated water content (cm^3 cm^{-3}), dry bulk density (g cm^{-3}), soil organic C content (wt. %), saturated hydraulic conductivity, soil pH, clay content (wt. % <0.002 mm particle size), and silt content (wt. % 0.002–0.05 mm particle size). The water content, bulk density, organic C and saturated hydraulic conductivity data were measured from intact cores (10 cm diameter by 10 cm long) collected from the 0 to 10, 10 to 20, 20 to 30 and 30 to 40 cm depths during 1999 and 2000 (unpublished data); the pH, clay and silt data were obtained from a soil survey report (Bryant et al. 1987). The data were used to construct the model soil profiles as indicated in Table 3. The DSSAT soil profile data also requires a maize root distribution/growth parameter (i.e. a factor from 0 to 1) (Stone et al. 1987), which was estimated here using the relationship: Root_growth_factor = 1.0 × exp (−0.02 LayerCentre), where LayerCentre is the depth from the soil surface to the centre of the soil layer in question (Gijsman et al. 2007). The root growth factor was set to 1.0 if the centre of the soil layer was ≤20 cm from the surface (Table 3).

Soil profile initial conditions for the start of the simulations (May 10, 1959) were estimated by running DSSAT for 3 years (May 1 1956 to May 9 1959) using 1956–1959 weather data and the soil physical data for CC-F (Table 3), and the soil mineral N (NH_4–N and NO_3–N) and water content profiles measured in CC-F during year 2000. Use of the CC-F data for establishing the initial conditions of both treatments (CC-F, CC-NF) is justified on the grounds that maize was grown on all plots for 3 years 1956–1958 after tile installation (1955) to ensure that tile flow was uniform across plots before the start of the cropping and fertilizer treatments. Once the soil profile initial conditions were established, the simulations were run from May 10, 1959 to Dec 31, 2008.

Model evaluation

Model performance was evaluated by comparing simulated and measured values of maize grain yields for the entire 50 year period, soil profile N distribution for 2008, and nitrate loss in tile drainage water for 1998–2000. The comparisons were quantified via the "EasyGrapher" program (Yang and Huffman 2004).

Deviation and test statistics have been used extensively in the past to assess DSSAT performance (e.g. Rinaldi et al. 2007; Timsina and Humphreys 2006), and the merits of deviation and test statistics have been reviewed by others (e.g. Kobayashi and Salam 2000; Loague and Green 1991; Willmott 1982; Yang et al. 2000). However, each deviation/test statistic addresses only a specific aspect of a model's performance and no single statistic provides an overall model evaluation. Hence, we employed three deviation statistics (root mean square error, RMSE, normalized-RMSE (n-RMSE), forecasting efficiency, EF) and one test statistic (coefficient of determination, R^2) in the evaluation of DSSAT-Maize. The deviation statistics were defined by:

$$\mathrm{RMSE} = \left[n^{-1} \sum_{i=1}^{n} (s_i - m_i)^2 \right]^{0.5} \quad (1)$$

Table 2 Monthly, growing season and annual precipitation from 1959 to 2008 at Woodslee, Ontario, Canada

Year	Jan (mm)	Feb (mm)	Mar (mm)	Apr (mm)	May (mm)	Jun (mm)	Jul (mm)	Aug (mm)	Sep (mm)	Oct (mm)	Nov (mm)	Dec (mm)	Growing season (mm)	Annual (mm)
1959	113	62	81	110	78	32	90	109	70	143	71	83	521	1,041
1960	82	79	37	46	76	133	53	43	21	39	34	19	365	663
1961	9	96	65	151	56	69	49	80	83	25	74	44	361	800
1962	66	63	39	31	36	51	154	87	68	58	57	33	454	743
1963	29	19	95	92	50	56	39	49	38	28	30	58	259	582
1964	90	21	124	130	54	95	52	123	40	8	23	67	372	826
1965	133	78	67	44	68	55	45	119	84	76	37	122	447	927
1966	23	39	44	90	47	75	159	112	79	36	123	138	506	963
1967	37	36	34	73	48	64	66	32	56	97	75	128	363	746
1968	110	24	85	54	175	100	124	43	36	53	106	122	530	1,030
1969	91	11	52	136	139	98	221	63	61	56	95	64	638	1,086
1970	26	32	69	132	73	85	125	20	48	55	74	48	405	786
1971	32	123	74	26	43	77	51	45	64	26	50	119	305	730
1972	51	31	88	98	55	58	66	158	86	53	121	95	475	959
1973	39	36	136	44	85	111	97	20	80	51	73	95	443	868
1974	66	60	106	63	98	54	33	29	48	20	110	110	281	795
1975	77	70	70	56	43	71	47	187	89	31	47	98	467	885
1976	80	156	112	63	100	80	45	12	102	69	16	27	408	861
1977	28	63	133	128	50	81	67	128	172	44	73	85	542	1,053
1978	112	9	50	85	76	100	52	30	76	61	55	82	396	788
1979	43	20	68	145	115	67	120	38	71	51	105	72	462	914
1980	28	26	23	74	55	145	160	97	69	65	24	64	591	830
1981	15	91	26	110	80	122	128	80	118	79	29	58	607	936
1982	104	43	60	53	18	63	47	32	78	41	184	96	280	821
1983	20	33	50	115	123	111	211	48	103	70	113	99	666	1,097
1984	25	47	94	67	101	59	38	68	111	68	64	89	445	830
1985	56	82	191	22	81	71	84	194	75	74	181	35	580	1,147
1986	6	41	26	78	61	160	106	82	157	91	59	79	657	946
1987	14	0	27	46	54	131	59	158	116	61	94	89	579	848
1988	21	55	30	49	14	23	110	96	88	32	104	33	363	655
1989	34	11	39	77	166	116	295	88	59	59	51	35	784	1,029
1990	36	173	43	62	91	59	49	117	200	93	42	145	609	1,110
1991	26	15	43	91	80	65	10	65	27	132	51	47	378	650
1992	34	44	70	90	50	67	122	126	134	50	130	55	547	968
1993	94	8	49	81	54	105	48	31	105	57	45	20	399	695
1994	74	41	53	90	33	83	31	112	41	56	53	43	356	710
1995	50	5	37	66	67	38	97	54	36	83	68	13	375	614
1996	29	28	45	76	69	67	54	18	197	58	35	42	463	717
1997	34	81	66	22	100	110	49	84	70	38	17	42	450	713
1998	53	72	66	93	33	48	64	128	25	32	25	13	328	651
1999	113	24	16	104	56	71	29	58	46	36	39	29	296	620
2000	15	20	39	73	100	130	136	96	122	79	42	92	662	942
2001	60	61	15	76	85	32	15	111	134	146	66	48	523	848
2002	58	35	45	101	104	90	62	21	43	55	82	45	376	742

Table 2 continued

Year	Jan (mm)	Feb (mm)	Mar (mm)	Apr (mm)	May (mm)	Jun (mm)	Jul (mm)	Aug (mm)	Sep (mm)	Oct (mm)	Nov (mm)	Dec (mm)	Growing season (mm)	Annual (mm)
2003	10	32	40	58	159	73	54	48	106	59	74	68	499	782
2004	40	22	92	42	170	75	93	121	20	56	77	79	535	887
2005	84	46	8	62	22	23	62	51	66	9	61	56	233	551
2006	71	49	54	64	104	67	108	76	60	113	77	80	528	924
2007	90	10	69	67	53	58	36	111	62	58	62	77	379	753
2008	57	74	69	27	54	186	86	13	125	29	95	78	492	893

$$\text{Normalized RMSE} = \frac{\text{RMSE}}{\bar{m}} \tag{2}$$

$$\text{EF} = \frac{\sum_{i=1}^{n} (m_i - \bar{m})^2 - \sum_{i=1}^{n} (s_i - m_i)^2}{\sum_{i=1}^{n} (m_i - \bar{m})^2} \tag{3}$$

where s_i and m_i are the simulated and measured values, respectively, n is the number of data points, and $\overline{\mathrm{m}}$ is the mean of the measured data. The RMSE measures the mean discrepancy between simulated and measured values with the same unit, while the normalized-RMSE removes the unit and therefore allows comparison of model performance among variables with different units. For model efficiency, EF = 1 indicates perfect correspondence between the simulated and measured data (i.e., $s = m$), while EF < 0 indicates that the simulated values (s) are worse than simply using the mean of m (i.e. $\overline{\mathrm{m}}$). The classical R^2 statistic ($1 \geq R^2 \geq 0$) gives the percentage of data variance accounted for by the model.

Model runs and outputs

When the DSSAT model is run, it accesses four input files in the following succession: management file, daily weather file (from 1959 to 2008), cultivar file (Table 4), and soil profile file (Table 3). The daily outputs from the model includes: crop growth (growth stage, LAI, biomass and grain yield, % N in grain and leaves), and for each soil layer, carbon, mineral N (NH_4^+–N and NO_3^-–N) and water content. There are also summary outputs, including: evaluation, overview and soil water balance. The outputs are readily visualized using graphical display packages within DSSAT tools (e.g. GBUILD), or by using EasyGrapher, a supporting software program (Yang et al. 2004).

Results and discussion

Cultivar calibration

Crop growth in the CSM- CERES-Maize model is controlled by phenologically defined growth stages, which are in turn driven by energy input in the form of growing degree-days (GDD) (Hoogenboom et al. 2003; Jones et al. 2003). Growth stages are defined in DSSAT in terms of cultivar coefficients, which are specific to both the crop cultivar and the local climate, and must therefore be individually calibrated. The CSM-CERES-Maize model uses 6 cultivar coefficients (Hoogenboom et al. 2003), three representing early growth (P1, P2 and P5), two representing grain filling (i.e., G2 and G3), and one representing the phylochron interval between successive leaf tip appearances (PHINT) (Table 4). Cultivar coefficients must be calibrated to meet the observed yield or biomass under a no stress growing condition, i.e. without water, heat or nutrient deficiencies (Boote 1999).

Four maize cultivars were calibrated over the 50 year simulation period to reflect changes in variety and planting density. As the cultivar record from 1959 to 1982 was incomplete, planting density records were used as a surrogate, i.e. 5.0 plants m^{-2} (1959–1965), 5.4 plant m^{-2} (1966–1982), 5.5 plant m^{-2} (1983–1996), and 6.2 plant m^{-2} (1997–2007). Furthermore, years 1961, 1975, 1986 and 2000 were selected for cultivar calibration because growing season precipitation from May to October of those years (i.e. 361, 467, 657 and 662 mm, respectively) indicated no significant water stress (Table 2).

Four expected average maize yield objectives were established based on maize dry yield, which was about 6,000 kg ha^{-1} in the 1960s with an average

Table 3 Soil profile data under continuous corn with fertilization (CC-F) and continuous corn without fertilization (CC-NF) treatments at Woodslee, Ontario Canada in 2000

Soil profile depth (cm)	0–10	10–20	20–30	30–40	40–60	60–150
Treatment	CC-F					
Lower limit (cm^3 cm^{-3})	0.207	0.306	0.314	0.241	0.241	0.241
Upper limit, drained (cm^3 cm^{-3})	0.341	0.380	0.368	0.334	0.334	0.334
Upper limit, saturated (cm^3 cm^{-3})	0.496	0.447	0.439	0.404	0.404	0.404
Root growth factor (0–1)	1.000	1.000	0.607	0.497	0.368	0.172
Sat. Hydraulic conductivity, macropore (cm h^{-1})	81.97	3.24	7.87	1.63	1.63	1.63
Bulk density (g cm^{-3})	1.35	1.46	1.55	1.61	1.61	1.61
Organic carbon (%)	2.50	2.50	1.00	1.00	0.40	0.40
Clay (<0.002 mm) (%)	37	45	45	45	45	45
Silt (0.05–0.002) (%)	38	34	34	34	34	34
pH in water	6.8	6.8	6.8	6.8	6.8	6.8
Treatment	CC-NF					
Lower limit (cm^3 cm^{-3})	0.240	0.312	0.297	0.309	0.309	0.309
Upper limit, drained (cm^3 cm^{-3})	0.365	0.379	0.389	0.379	0.379	0.379
Upper limit, saturated (cm^3 cm^{-3})	0.451	0.434	0.432	0.428	0.428	0.428
Root growth factor (0–1)	1.000	1.000	0.607	0.497	0.368	0.172
Sat. Hydraulic conductivity, macropore (cm h^{-1})	9.62	0.05	0.04	4.89	4.89	4.89
Bulk density (g cm^{-3})	1.52	1.51	1.53	1.51	1.51	1.51
Organic carbon (%)	1.70	1.70	0.93	0.59	0.59	0.59
Clay (<0.002 mm) (%)	37	45	45	45	45	45
Silt (0.05–0.002) (%)	38	34	34	34	34	34
pH in water	6.8	6.8	6.8	6.8	6.8	6.8

yield increase of 1.7% per year, 7,000–8,000 kg ha^{-1} in the 1970–1980 period, and about 10,000 kg ha^{-1} in the 2000s (Drury and Tan 1995; Tollenaar and Wu 1999). Using these statistics, expected average maize dry yields for calibration years were arbitrarily set at 6,200 kg ha^{-1} for 1961, 7,500 kg ha^{-1} for 1975, 8,200 kg ha^{-1} for 1986 and 10,000 kg ha^{-1} for 2000 with optimal fertilizer N application rates set between 120 and 200 kg N ha^{-1}(Table 4).

Soil profile data listed in Table 3 under CC-F plot is a clay soil with water stress on crop growth and are not suitable for representing an 'ideal' soil in South Ontario that has less water stress for corn growth. An "ideal" soil profile for calibrating the cultivar coefficients was created by arbitrarily reducing the wilting point water content of the CC-F soil profile (Table 3) by 5, 10,15, 20 and 25% to prevent crop water stresses during the calibration years (especially during the grain filling stage). After running the CERES-Maize model for above sensitivity simulations, With the 25% reduction of the wilting point water content of the CC-F soil profile, simulated crop growth during the calibration years showed no water stress and produced good agreement between the simulated and expected average maize yields. Hence, the ideal soil profile was used for calibrating the cultivar coefficients.

A default Pioneer maize cultivar (PIO 0069) was selected for the calibration because it was well suited for the Southwestern Ontario climate and ecological zone. Four crop management files were set up for each calibration year, and a cultivar coefficient calculator program (*GenCalc* V2.0) developed by Hunt et al. (1993) was used to calibrate coefficients firstly by growth period (P1, P2 and P5), and secondly by filling rate (G2) and kernel numbers per plant (G3). The model's outputs were compared with the measured data for each iteration and the coefficients were changed in sequence until the simulated and the measured values showed the best match (i.e. the smallest RMSE). After calibration of

Table 4 The calibrated maize cultivar coefficients using a simulated N application rate of 240 kg N ha^{-1} using DSSAT v4.5[a]

Cultivar	Default	Calibrated coefficients for calibration year			
Calibration year		1961	1975	1986	2000
Cultivar name	IB0069[b]	IB1961	IB1975	IB1986	IB2000
Cultivar coefficients					
P1 Time from seedling emergence to the end of the Juvenile (degree days >8°C)	212.4	212.4	212.4	233.5	224.8
P2 Extent to which development (expressed as days) is delayed for each hour (hour increase in photoperiod > the longest photoperiod 12.5 h)	0.52	0.52	0.52	0.57	0.52
P5 Thermal time from silking to physiological maturity	792.8	840.0	890.4	840	792.8
G2 Maximum possible number of kernels per plant	625.0	722.6	722.6	722.6	681.8
G3 Kernel optimum filling rate during the linear grain filling stage (mg day^{-1})	6.0	7.62	6.94	8.02	7.95
PHINT Phylochron interval between leaf tip to emerge (degree days)	38.9	38.9	38.9	38.9	38.9
Simulated crop yield and growing days					
Growing period (day)		145	148	157	166
Simulated dry yield (Y sd) by default cultivar (kg ha^{-1})		4,123	4,107	8,445	7,088
Simulated dry yield (Ysc) by calibrated cultivar (kg ha^{-1})		6,252	7,431	8,176	10,609
Average yield (Ym) with no stress in Ontario (kg ha^{-1})		6,200	7,500	8,200	10,000
Percent difference					
Difference (Ysd − Ym)/Ym by default cultivar (%)		−33.5	−45.2	3.0	−29.1
Difference (Ysc − Ym)/Ym by calibrated cultivar (%)		0.8	−0.9	−0.3	6.1

[a] DSSAT v4.5 β version (updated on Aug 19, 2009) was used for cultivar calibration and all maize sequence simulation study in this paper

[b] IBO0069 represents maize cultivar PIO 3790 (Pioneer 3790)

the cultivar coefficients, good agreement (i.e., percent difference) was obtained between simulated and measured maize grain yield by using the calibrated cultivar coefficients (Table 4).

Maize radiation use efficiencies, RUE, (g dry grain matter MJ^{-1} incident solar energy) commonly varies with cultivars, i.e., the maize RUE in Ontario, Canada might increase from 1.95 to 3.78 g MJ^{-1} (Tollenaar and Aguilera 1992). When we simulated 50 year CC-NF field experiment using the default RUE value (4.2 g MJ^{-1}) in DSSAT, we found that the simulated corn yields were systematically higher than the measured data. Other studies indicated that RUE might also be affected by environmental condition, such as soil fertility (Muchow 1994; Greenwald et al. 2006), but the model might not account for this stress properly. Data in Table 3 also showed that the CC-F soil was relatively constant while that of CC-NF declined over time (i.e., bulk density increased and soil organic carbon declined), Therefore, the default RUE value (4.2 g MJ^{-1}) in DSSAT was calibrated to a constant value of 3.9 g MJ^{-1} for CC-F (all years), while that for CC-NF was 3.9 g MJ^{-1} for 1959–1967 at which time yields declined to very low values (typically <2 t ha^{-1}), and then re-calibrated using a RUE of 2.3 g MJ^{-1} for 1968–2008.

Yield evaluation

The simulated and measured maize grain yields for CC-F and CC-NF from 1959 to 2008 are displayed in Fig. 1. Both the simulated and measured yields are substantially greater for the CC-F treatment (Fig. 1a) than for CC-NF (Fig. 1b). The annual fluctuation of maize yield was reasonably simulated in CC-F for all years, and in CC-NF for 1959–1970, but not reasonably simulated in CC-NF after 1970. The similar yields between CC-F and CC-NF during 1959–1965

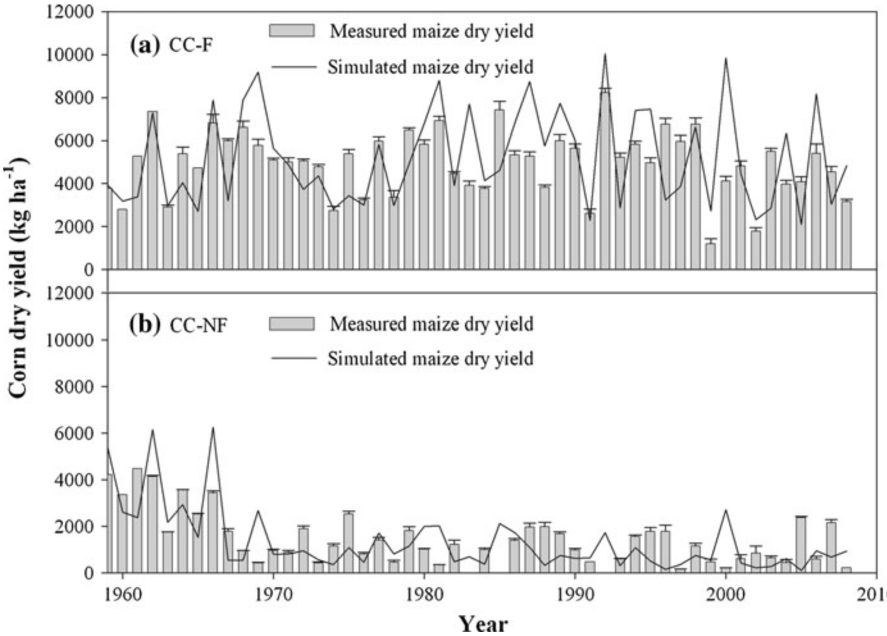

Fig. 1 Comparison of simulated and measured maize grain yield from 1959 to 2008 under CC-F (**a**) and CC-NF (**b**) treatments at Woodslee, Ontario, Canada; *Vertical bars* were SE

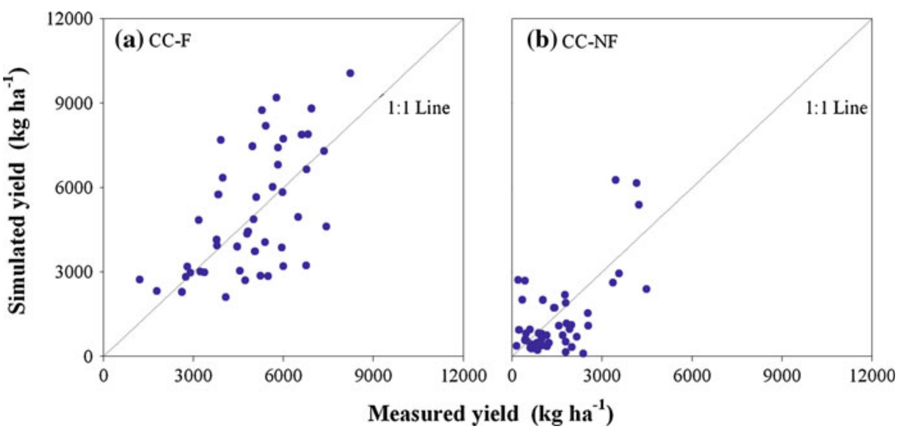

Fig. 2 Correlation between measured and simulated maize dry yield under CC-F (**a**) and CC-NF (**b**) treatments by DSSAT model from 1959 to 2008 yield at Woodslee, Ontario, Canada

probably occurred because the soil condition remained roughly equivalent between the two treatments during the first 5–6 years of the experiment. After 1965, however, the lower yields in CC-NF undoubtedly reflect both the reduction in soil fertility and the decline in overall soil quality in this treatment as a result of no fertilization and reduced amounts of crop residues returned to the soil.

The deviations between simulated and measured annual maize grain yields were rather large for both CC-F (RMSE = 1,391 kg ha^{-1}) and CC-NF (RMSE = 1,166 kg ha^{-1}) (Fig. 2; Table 5), but were on the same order as those obtained by others (Sadler, et al. 2000; Ma et al. 2007). Note also that the n-RMSE values were 39% for CC-F and 82% for CC-NF, indicating a substantially larger uncertainty in simulated annual yields for CC-NF than for CC-F. Figure 2 shows, however, that the simulated annual yields are scattered more or less equally about the 1:1 line for both treatments, indicating that there were no systematic deviations in the model simulations, and that the 50-year average annual yield was simulated reasonably well for both treatments (Table 5). The imprecise simulation of annual yield fluctuations probably reflects factors and/or events that are not considered in the model, such as extreme short-duration weather

Table 5 Statistical evaluation of annual grain yield, soil mineral N and soil nitrate loss

Measured data	RMSE[a]	n-RMSE[b]	EF[c]	R^2	Samples
	CC-F				
Annual grain yield (kg ha^{-1})	1,391	39%	−0.70	0.36	50
Soil-N 0–15 cm (mg kg^{-1})	13.0	66%	0.49	0.94	6
Soil-N 0–30 cm (mg kg^{-1})	2.0	58%	−0.12	0.46	6
Nitrate–N loss (kg ha^{-1})	12.8	29%	0.64	0.93	19
	CC-NF				
Maize dry yield (kg ha^{-1})	1,166	82%	−0.50	0.40	50
Soil-N 0–15 cm (mg kg^{-1})	2.0	89%	−1.2	0.62	6
Soil-N 0–30 cm (mg kg^{-1})	1.3	64%	0.04	0.26	6
Nitrate–N loss (kg ha^{-1})	8.2	160%	−8.0	0.86	19

[a] RMSE represents Residual Mean Square Error, see Eq. 1 for details

[b] n-RMSE represents normalized RMSE, see Eq. 2 for details

[c] EF represents Forecasting Efficiency, see Eq. 3 for details

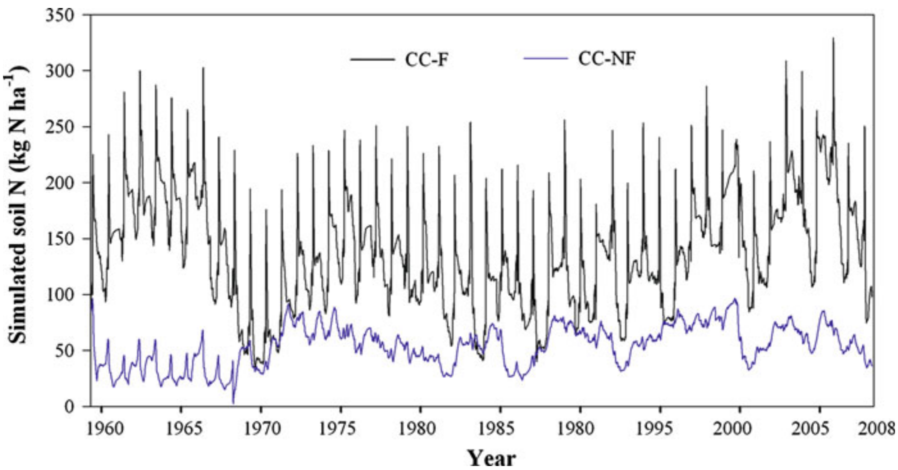

Fig. 3 Simulated soil mineral N (NH_4–N + NO_3–N) from 1959 to 2008 under CC-F and CC-NF at Woodslee, Ontario, Canada

events (e.g. sudden heavy rainfalls, high winds, hail damage, short-term water deficits/surpluses at critical times, etc.).

The large differences between simulated and measured annual maize yields may be related to our assumptions regarding soil physical properties, cultivar characteristics and land management. DSSAT sequential simulation model assumed no changes on soil physical parameters from beginning to the end (i.e., from 1959 to 2008), but the model simulates soil nutrients without set up default parameters each year. This way, soil water content, soil carbon and nitrogen dynamics were simulated continuously from 1959 to 2008. Simulated total soil organic C decreased by 5.3 and 12.3% in CC-F and CC-NF treatments, respectively over 50 year time and simulated soil mineral N showed significant changes over time (Fig. 3), indicating that the higher soil mineral N was found ranging from 100 to 300 kg N ha^{-1} in CC-F plot, while soil mineral N was below 100 kg N ha^{-1} in the CC-NF treatment. In fact, the measured soil physical properties (especially for CC-NF), such as, soil water contents at wilting point, at field capacity and at saturated condition, bulk density and percentages of clay and silt etc. changed significantly during 50 years continuous maize cultivation, and this was evidenced from the measured data (Table 3) in 2000, while the model used constant soil physical properties over the 50 years. The calibrated "average" cultivar coefficients may not have been appropriate for every year due to weather variations (White 1998; Xue et al. 2004; Langensiepen et al. 2008). Crop growth simulations can be very sensitive to short-term changes in root zone moisture content (Lobell and Ortiz-Monasterio 2006). Maize yield is known to be effected by planting date (Anapalli et al. 2005; Soler et al. 2007), and in our simulations, a single date (May 10) had to be assumed for each year before 1983, as no planting date records were available (Table 1). Grain yield at the field site was known to be significantly related to growing season precipitation (Drury and Tan 1995). Table 2 data showed that larger variations of growing season rainfall were found to range from 233 mm in 2005–784 mm in 1989. From the fitted equation $Ym = 16.982\ X - 0.0126\ X^2$ ($R^2 = -0.02$), where Ym = the measured corn yield and X = growing season rainfall (mm), we could obtain the maximum grain yield (Ym) of 5,722 kg ha^{-1} at growing season rainfall of 673 mm with a small $R^2 < 0.02$, indicating that crop yield was not only affected by growing season rainfall. However, the fitted equation $Ys = -418 + 12.17\ X(R^2 = 0.42)$, where Ys = the simulated corn yield, indicating that the DSSAT simulated corn yield (Ys) linearly with growing season rainfall and it did not account for other effects such as flooding at higher rainfall precisely, etc.

Soil mineral N evaluation

The DSSAT Century-based soil model simulated vastly different soil N curves under CC-F and CC-NF (Fig. 3), which are presumed to reflect changes in soil temperature, water content, carbon content, microbiological processes, etc. between the two treatments. Due to no fertilization, the simulated soil N under CC-NF was significantly lower in both magnitude and annual variation than under CC-F. For example, the results of the simulated soil mineral N (NH_4–N + NO_3–N) in the 0–150 cm depth fluctuated from about 50–350 kg N ha^{-1} under CC-F, whereas the simulation in mineral N under CC-NF ranged from only 5–100 kg N ha^{-1}.

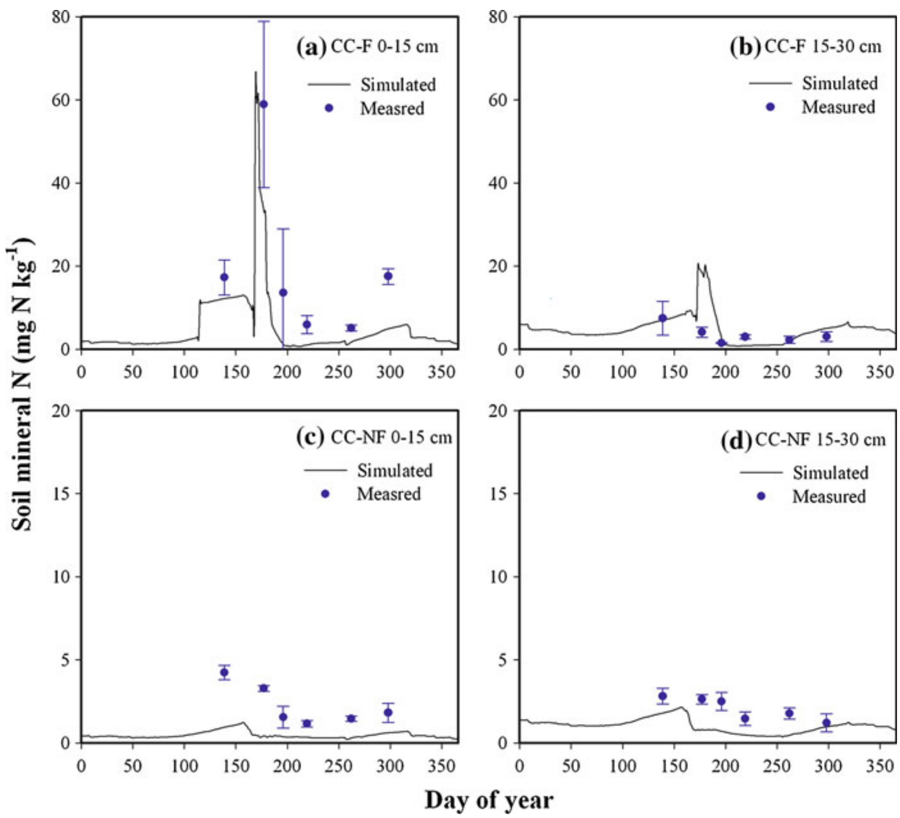

Fig. 4 Measured and simulated soil mineral N content under CC-F [(**a**) and (**b**)] and CC-NF [(**c**) and (**d**)] plots in 2008 at Woodslee, Ontario, Canada; Vertical bars were SE

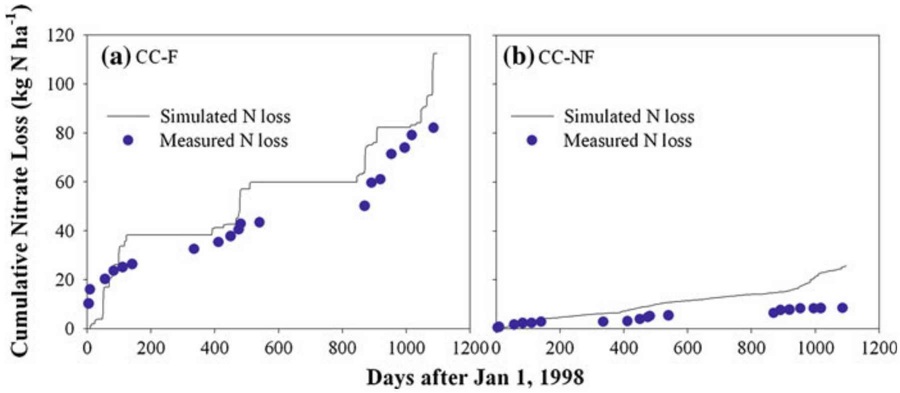

Fig. 5 Simulated and measured cumulative nitrate loss through sub-surface tiles under CC-F and CC-NF treatments from Jan 1998 to Dec 2000 at Woodslee, Ontario, Canada

Soil mineral N in the top layer

The measured and simulated soil mineral N contents in the 0–15 cm and the 15–30 cm layers during 2008 were plotted in Fig. 4a and b for the CC-F treatment, and in Fig. 4c and d for CC-NF. The simulated soil mineral N tracked the measurements reasonably well for CC-F (Fig. 4a, b), and it is noted that both simulated and measured soil mineral N reached 60 kg N ha^{-1} in the 0–15 cm depth after N side-dressing on June 12. Both simulated and measured soil mineral N in the CC-NF treatment were very small (<5 kg N ha^{-1}) as a result of many years with no fertilizer N application. The n-RMSE values ranged 58–66% for CC-F and 64–89% for CC-NF, indicating large uncertainty associated with simulation of soil mineral N content, which is perhaps not surprising, given the complexity of soil N dynamics.

Soil nitrate leaching

Nitrate leaching through sub-surface tiles not only results in environment pollution, but also represents an economic loss to the producers. Nitrate leaching was influenced by crop or fallow frequency, fertilizer N rate, precipitation, soil texture and types of crop. The simulated annual nitrate loss through tile drainage from CC-F was 2–3 times larger than from CC-NF, as might be expected (Fig. 5). For the CC-F treatment, simulated cumulative nitrate leaching through tile drainage from 1998 to 2000 showed generally good visual (Fig. 5a) and quantitative (n-RMSE = 29%) agreement with measurements, but the model consistently overestimated cumulative nitrate loss from CC-NF (Fig. 5b, n-RMSE = 160%).

Conclusions

The CSM–CERES-Maize model was evaluated using a long-term (1959–2008) continuous maize experiment in southern Ontario on a clay loam soil. Although the model did not simulate the annual maize yield precisely (Figs. 1, 2), the model simulated crop yields were as good as other researchers that have obtained. The model simulated soil N content and leaching losses less well than yield, as might be expected, with consistent overestimates for CC-NF. The overestimation of both maize yield and soil N for CC-NF may reflect inadequate model representation of the degraded soil profile under that treatment.

We suggest that sequence analysis with DSSAT should use more than one soil profile for long-term simulations, or that modifications be made to allow the model to update soil physical profile characteristics during long-term simulations. We also recommend that short-term but large impact disturbances, such as soil erosion, high winds, flooding, hail damage and insect/weed infestations, be integrated into the model to evaluate the both the immediate and cumulative effects of short-term extreme events.

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