Published online July 6, 2006

Simulating Long-Term and Residual Effects of Nitrogen Fertilization on Corn Yields, Soil Carbon Sequestration, and Soil Nitrogen Dynamics

X. He, R. C. Izaurralde, M. B. Vanotti, J. R. Williams, and A. M. Thomson*

ABSTRACT

Soil carbon sequestration (SCS) has the potential to attenuate increasing atmospheric CO_2 and mitigate greenhouse warming. Understanding of this potential can be assisted by the use of simulation models. We evaluated the ability of the EPIC model to simulate corn (*Zea mays* L.) yields and soil organic carbon (SOC) at Arlington, WI, during 1958–1991. Corn was grown continuously on a Typic Argiudoll with three N levels: LTN1 (control), LTN2 (medium), and LTN3 (high). The LTN2 N rate started at 56 kg ha^{-1} (1958), increased to 92 kg ha^{-1} (1963), and reached 140 kg ha^{-1} (1973). The LTN3 N rate was maintained at twice the LTN2 level. In 1984, each plot was divided into four subplots receiving N at 0, 84, 168, and 252 kg ha^{-1}. Five treatments were used for model evaluation. Percent errors of mean yield predictions during 1958–1983 decreased as N rate increased (LTN1 = −5.0%, LTN2 = 3.5%, and LTN3 = 1.0%). Percent errors of mean yield predictions during 1985–1991 were larger than during the first period. Simulated and observed mean yields during 1958–1991 were highly correlated (R^2 = 0.961, $p < 0.01$). Simulated SOC agreed well with observed values with percent errors from −5.8 to 0.5% in 1984 and from −5.1 to 0.7% in 1990. EPIC captured the dynamics of SOC, SCS, and microbial biomass. Simulated net N mineralization rates were lower than those from laboratory incubations. Improvements in EPIC's ability to predict annual variability of crop yields may lead to improved estimates of SCS.

The concentration of carbon dioxide (CO_2) in the atmosphere continues to grow unabated because of fossil fuel combustion and land use changes (Intergovernmental Panel on Climate Change, 2001). The continued accumulation of CO_2 and other greenhouse gases, such as methane (CH_4) and nitrous oxide (N_2O), in the atmosphere generates concern because of their anticipated impact on the global climate. Soil carbon sequestration (SCS), attainable through adoption of no-tillage management and conversion of agricultural land to native vegetation among other practices, has emerged as a viable technology to attenuate the rate of increase of atmospheric CO_2 and thus contribute to mitigating global warming (Cole et al., 1996; Janzen et al., 1998; Lal et al., 1999; Allmaras et al., 2000; Post and Kwon, 2000; Smith et al., 2000; Izaurralde et al., 2001b; Kucharik et al., 2001). An early deployment of SCS could play an early role in atmospheric CO_2 stabilization and allow for other cost-effective and non-carbon-emitting energy technologies (e.g., hydrogen, wind, and solar energy) to be developed (Izaurralde et al., 2001a). To succeed, SCS has to meet production, environmental, and economic criteria. Post et al. (2004) proposed a methodology to evaluate whether the widespread adoption of a particular SCS practice is technically useful, environmentally acceptable, and economically cost effective.

Agroecosystem and soil organic matter models can contribute toward understanding and applying SCS practices. Smith et al. (1997) tested and compared nine soil organic matter models in their ability to simulate changes in SOC concentrations observed in long-term experiments from temperate zones covering grassland, cropping, and woodland use. Statistical tests of the simulation results allowed for the identification of a group of six models with superior performance over the rest. Testing of models against experimental datasets is an essential step toward evaluating the performance of a model as a whole or a set of its components. The Environmental Policy Integrated Climate (EPIC) model (Williams, 1995), originally named Erosion Productivity Impact Calculator, is an agroecosystem model capable of simulating crop growth as a function of weather, soil, and management conditions (e.g., tillage, fertilization, irrigation, crop rotations), as well as many other processes related to managed ecosystems (e.g., wind and water erosion, water balance, pesticide fate, etc.). Recently, Izaurralde et al. (2006) developed in EPIC algorithms to describe the coupled cycling of C and N in soils. These algorithms are based on the approach used in the Century model to describe soil C and N dynamics (Parton et al., 1987, 1993, 1994). The resulting model is thus capable of simulating soil C and N dynamics as affected by the interacting effects of weather, soil, management, and erosion.

EPIC has been evaluated and used worldwide under many types of management practices and climate–soil conditions. For example, EPIC has been used to evaluate cropping systems and crop yields in Argentina (Bernardos et al., 2001), France (Cabelguenne et al., 1990), and Jordan (Hughes et al., 1995). It has also been used to estimate soil erosion (Kelly et al., 1996; Poudel et al., 2000) and N uptake (Cavero et al., 1999). The water balance component in EPIC has been used to predict soil water content (Costantini et al., 2002), irrigation timing and amount (Rinaldi, 2001), runoff and P losses (Pierson et al., 2001), and nitrate leaching (Chung

X. He, R.C. Izaurralde, and A.M. Thomson, Joint Global Change Research Institute, Pacific Northwest National Laboratory, University of Maryland, 8400 Baltimore Avenue, Suite 201, College Park, MD 20740. M.B. Vanotti, USDA-ARS, South Atlantic Area, Coastal Plains Soil, Water, and Plant Research Center, 2611 West Lucas Street, Florence, SC 29501. J.R. Williams, Texas A&M University, Blacklands Research Center, 808 East Blacklands Road, Temple, TX 76502. Received 28 June 2005. *Corresponding author (allison.thomson@pnl.gov).

Published in J. Environ. Qual. 35:1608–1619 (2006).
Special Submissions
doi:10.2134/jeq2005.0259

677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: D_b, bulk density; EPIC, Environmental Policy Integrated Climate; HI, harvest index; LAI, leaf area index; NMN, net nitrogen mineralization; RMSE, root mean square error; RUE, radiation use efficiency; SCS, soil carbon sequestration; SOC, soil organic carbon; SOM, soil organic matter.

et al., 2001). With increased awareness of climate change issues, EPIC has been increasingly used to simulate the impacts of climate change and elevated atmospheric CO_2 on agricultural production and ecosystem processes (Stockle et al., 1992a, 1992b; Favis-Mortlock et al., 1991; McKenney et al., 1992; Easterling et al., 1996; Lee et al., 1996; Phillips et al., 1996; Brown and Rosenberg, 1997; Dhakhwa et al., 1997; Brown and Rosenberg, 1999; Brown et al., 2000; Tan and Shibasaki, 2003; Izaurralde et al., 2003).

Izaurralde et al. (2006) conducted two tests of the new C and N modules in EPIC using experimental data of different duration. In one simulation experiment, the model correctly approximated changes in SOC observed in four out of five cases when converting agricultural land into perennial vegetation cover. In another, EPIC accounted for 69% of the variability in grain yields, 89% of the variability in C inputs, and 91% of the variability in SOC content observed in a 61-yr experiment. Further tests are needed to ensure its applicability to a wide range of environmental and management conditions.

In a previous paper, Wang et al. (2005) used data from a 34-yr long-term experiment from Arlington, WI (Vanotti et al., 1997) to conduct uncertainty and sensitivity analyses of EPIC in its predictions of corn yields and SOC dynamics. Here we extend our analysis of the Vanotti et al. (1997) data set by conducting a comprehensive evaluation of EPIC for simulating a suite of agroecosystem processes including (i) crop yield and stress, (ii) SOC and total soil N dynamics, (iii) soil microbial biomass, and (iv) net nitrogen mineralization (NMN). In addition, the results will be used to compare observed vs. simulated SCS rates as a function of N rate application.

MATERIALS AND METHODS

Model Description

The EPIC model consists of nine integrated submodels: hydrology, weather, erosion, carbon and nutrient cycling (N, P, and K), plant growth, soil temperature, tillage, economics, and plant environment control. In its current form, EPIC is well suited for assessing the effects of soil erosion on crop productivity, predicting the effects of management decisions on soil, water, nutrient, and pesticide movements, and tracing the allocation and turnover of C and N in soil. The model operates on a daily time step and is capable of long-term simulations of up to 4000 yr with soil profiles having up to 15 layers.

Crop Growth Model

A single plant growth model is used in EPIC to simulate biomass accumulation and crop yield of about 100 crops, each with a unique set of growth parameters (e.g., radiation use efficiency, RUE; potential harvest index, HI; optimal and minimum temperatures for growth; maximum leaf area index, LAI; and stomatal resistance). EPIC is capable of simulating growth for both annual and perennial crops. Annual crops grow from planting date to harvest date or until the accumulated heat units equal the potential heat units for the crop (Williams, 1995). EPIC estimates crop yields by multiplying aboveground biomass at maturity by a harvest index. For nonstressed conditions, the harvest index is affected only by the heat unit index. The final HI is estimated based on the potential HI, minimum harvest index, and water use ratio. The model estimates potential biomass based on the interception of solar radiation and the RUE that is affected by vapor pressure deficit and by atmospheric CO_2 level.

Water, nutrient, temperature, aeration, and radiation stresses restrict daily accumulation of biomass, root growth, and yield (Williams, 1995). Stress factors are calculated daily and range from 0.0 to 1.0. For plant biomass, the stress used on a given day is the minimum of the water, nutrient, temperature, and aeration stresses. For root growth, it is the minimum of the calculated soil strength, temperature, and aluminum toxicity stresses. Crop yield reductions are calculated through water stress–induced reductions of the HI.

Carbon and Nitrogen Cycling Model

Like the Century model (Parton et al., 1987, 1993, 1994; Vitousek et al., 1994), EPIC allocates C and N into five pools (Izaurralde et al., 2006). Carbon added to soil as plant residues, roots, or animal manure is partitioned into structural and metabolic C according to lignin and N content. The C in structural and metabolic components of litter is subsequently distributed into the various kinetic compartments of increasing turnover time (biomass, slow, and passive) or evolved as CO_2. Losses of C and N can occur in solid form when wind and water erosion are simulated or in soluble form during runoff and leaching events. There are at least four major differences between Century and EPIC regarding organic transformations: (i) leaching equations in EPIC are used to move organic materials from surface litter to subsurface layers; (ii) temperature and water controls affecting transformation rates are calculated with equations currently in EPIC; (iii) the surface litter fraction in EPIC has a slow compartment but no passive compartment; and (iv) lignin concentration in EPIC is modeled as a sigmoidal function of plant age.

Initially, the model calculates potential transformations based on substrate-specific rate constants, temperature, and water content. Lignin content and soil texture also affect some of these transformations (e.g., structural litter and biomass). These transformations are considered potential because they reach completion only when sufficient quantities of organic and inorganic N are available. Actual transformations are calculated based on the N supply available from each potential transformation. The demand for N is established by the potential C transformation of the source compartment and the C to N ratio of the receiving compartment. If the N available exceeds the demand in all its receiving compartments, the potential transformation then becomes the actual transformation. Thus, the calculated N and C flows are added to the receiving compartment and subtracted from the source compartment. A net demand for mineral N is generated when the N available from a transformation is less than that demanded by flows to the receiving compartments. This net demand is calculated by subtracting the N in the potential transformation of the source compartment from the sum of the N required for the receiving compartments. The submodel then adds all the net demands for mineral N—including plant uptake—and compares this sum with the mineral N available. If the sum of the net N demands is less than the total mineral N, then each net N demand is met, allowing each potential transformation to become the actual transformation. When the total N demand exceeds the mineral N available, then the submodel calculates a proportional reduction in the net demand and each potential transformation. The sum of net demands is finally subtracted from the total mineral N. Equations and further details regarding these transformations are provided in Izaurralde et al. (2006).

Table 1. Nitrogen fertilization rates. The term LTN indicates long-term N fertilizer rates before 1984, and N indicates 1984–1991 N rates.

Plot	LTN1				LTN2				LTN3			
	kg N ha^{-1}											
1958–1962	0				56				112			
1963–1972	0				92				184			
1973–1983	0				140				280			
	LTN1-N0	LTN1-N84	LTN1-N168	LTN1-N252	LTN2-N0	LTN2-N84	LTN2-N168	LTN2-N252	LTN3-N0	LTN3-N84	LTN3-N168	LTN3-N252
1984–1991	0	84	168	252	0	84	168	252	0	84	168	252

Dynamic Atmospheric Carbon Dioxide

The EPIC model has a built-in equation to simulate the historical changes in atmospheric CO_2 concentration since 1880 (Izaurralde et al., 2006). For static CO_2 simulations, the model simply takes the user input value. For dynamic CO_2 simulations, the CO_2 concentration is calculated as a function of year. Before 1905, CO_2 is set to 280 ppmv. After 1905, $CO_2 = 280.33 - (\text{year} - 1880) \times [0.1879 - (\text{year} - 1880) \times 0.0077]$ (Keeling and Whorf, 2004).

Dynamic Soil Bulk Density

Soil organic matter (SOM) directly affects the soil bulk density (D_b). Increases in SOM decrease D_b. To simulate the D_b dynamics caused by changes in SOM, Izaurralde et al. (2006) added equations into EPIC to adjust D_b on a yearly basis according to the relationship formulated by Adams (1973):

$$D_b = \frac{100}{\dfrac{\text{SOC}\times 1.724}{0.244} + \dfrac{100-\text{SOC}\times 1.724}{\rho_m}}$$

$$0 \le \text{SOC} < 58(\text{g C kg}^{-1} \times 10^{-1})$$

$$D_b = 0.244;\ \text{SOC} = 58\ (\text{g C kg}^{-1} \times 10^{-1})$$

where SOC is soil organic carbon, 0.244 Mg m^{-3} is the bulk density of SOM, and ρ_m is mineral bulk density.

Experimental Data

Data for the simulation experiment were reported by Vanotti and Bundy (1996) and Vanotti et al. (1997) when studying the effects of long-term N fertilization on crop productivity and SOM dynamics. The experimental site was established in 1958 at Arlington, Wisconsin (43°18′ N, 89°21′ W) on the University of Wisconsin Arlington Agricultural Research Station. The site is located on a Plano silt loam (fine-silty, mixed, mesic Typic Argiudoll) and experiences a humid continental climate with mean annual precipitation of 791 mm and mean annual temperature of 7.6°C. The site, which is part of an extended plain with 1 to 2% slope, was originally covered by prairie vegetation and cultivated for approximately 25 yr before the establishment of the experiment using conventional tillage methods that included burning of corn stalks before plowing.

The study was designed to evaluate continuous corn responses to three N fertilization treatments: LTN1 for control (0 kg N ha^{-1}), LTN2 for medium N application rate (56 kg N ha^{-1}), and LTN3 for high N application rate (112 kg N ha^{-1}). The medium rate represented the recommended N rate for corn production at the beginning of the trial and was raised to 92 and 140 kg N ha^{-1}, respectively, in 1963 and 1973. The high N rate was maintained at twice the medium rate throughout the experiment. The treatments were arranged in a randomized complete block design with four replicates. The four replicate blocks were 60 × 36 m separated by 6-m-wide grassed alleyways. At the beginning of the experiment, each block was divided into three 60- × 12-m plots and each of the three N treatments was applied to one of the plots. In 1984, the long-term N treatments were discontinued and each original plot was split into four 15- × 12-m subplots with N rates of 0, 84, 168, and 252 kg N ha^{-1} to study the residual effects of previous N treatments. These short-term N treatments since 1984 were represented as N0, N84, N168, and N252.

The N fertilizer was applied as ammonium nitrate from 1958 to 1962, anhydrous ammonia from 1963 to 1983, and urea from 1984 onward. All the plots also received starter fertilizer (6–24–24) at planting. The starter fertilizer was drilled 5 cm below and 5 cm to the side of the seed at rates of 8, 15, and 21 kg N ha^{-1}, respectively, for control, medium, and high rate plots from 1958–1962 and rates of 13 kg N ha^{-1} for all the plots since 1963.

Corn was planted each year during the first and fourth week of May at a planting density of approximately 60000 to 70000 plants ha^{-1} and harvested in the fourth week of October, with corn residues returned to the soil by moldboard plowing in the next spring. The crop was harvested every year. The grain yield was measured at 15.5% moisture every year except during 1963–1967.

In 1985, each subplot was further split in two to evaluate the lime effects on crop yield. The lime application treatments were not included in this validation. Out of the 12 N treatments without lime application in Table 1, we chose five representative treatments of LTN1-N0, LTN2-N0, LTN3-N0, LTN2-N84, and LTN3-N168 to validate the model.

Model Input Preparation

Weather

A 34-yr (1958–1991) database of daily records of precipitation (mm), maximum and minimum temperature (°C), solar radiation (MJ m^{-2}), relative humidity (as fraction), and wind speed (m s^{-1}) and direction was used in the model validation. Figure 1 gives the annual means of daily air temperatures and annual precipitation from 1958 to 1991. The annual means of daily maximum temperature ranged from 12.1 to 15.5°C while those for minimum temperature ranged from 0.7 to 4.0°C. The

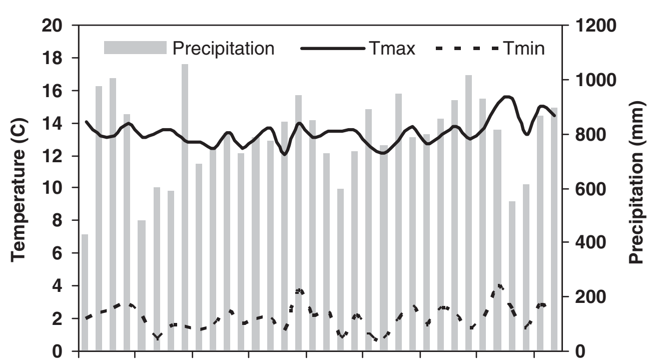

Fig. 1. Annual means of daily temperatures and total precipitation at Arlington, WI.

Table 2. Monthly weather parameters.

	January	February	March	April	May	June	July	August	September	October	November	December
Maximum temperature, °C	−4.21	−1.44	5.08	14.30	21.37	26.09	28.24	27.08	22.49	15.77	6.63	−1.41
Minimum temperature, °C	−13.66	−11.30	−4.90	1.83	7.78	12.70	15.42	14.34	9.91	4.09	−2.63	−10.14
Precipitation, mm	23.40	22.28	46.50	74.12	79.13	90.45	89.69	96.28	106.42	65.94	53.87	33.69
Solar radiation, MJ m^{-2}	6.65	10.11	13.65	17.23	20.93	22.95	22.62	19.61	14.89	10.35	6.32	5.29
Relative humidity	0.75	0.73	0.72	0.66	0.66	0.68	0.71	0.75	0.76	0.73	0.77	0.78
Wind velocity, m s^{-1}	4.41	4.31	4.59	4.7	4.09	3.74	3.31	3.22	3.54	4.06	4.39	4.28

34-yr means of daily maximum and minimum temperatures were 13.4 and 2.0°C, respectively. Annual precipitation ranged from 431 mm in 1958 to 1059 mm in 1965 with a mean value of 792 mm. Daily values of precipitation, air temperature (maximum and minimum), solar radiation, and relative humidity were processed by a stand-alone program to generate weather parameters needed to run EPIC (Table 2).

Soil

The soil at the site is a dark well-drained Plano silt loam. The soil properties were determined in 1958 at the beginning of the experiment. Soil bulk density was measured as 1.47 and 1.49 g cm^{-3}, respectively, for depths of 0 to 20 and 20 to 30 cm. The soil water content at wilting point and field capacity were measured to a depth of 90 cm at 30-cm depth intervals. Wilting points were 0.18, 0.20, and 0.22 m^3 m^{-3} for depths of 0 to 30, 30 to 60, and 60 to 90 cm, respectively, and field capacity values were 0.33, 0.34, and 0.35 m^3 m^{-3}, respectively. To study the effect of N fertilizer on soil properties, soil pH, SOC, and N were measured in 1958, 1984, and 1990 (Table 3). Soil organic C was determined using a modified Mebius procedure (Yeomans and Bremner, 1988) and total organic N by micro-Kjeldahl digestion (Nelson and Sommers, 1972). Microbial biomass C and N were measured only in 1990 by the chloroform fumigation–incubation method (Jenkinson and Powlson, 1976). Net N mineralization rates were calculated with data from a 40-wk aerobic leaching–incubation experiment maintained at 35°C on 1990 soil samples (Stanford and Smith, 1972). Values for 1958 are means of 12 replicates with four replicates for each N treatment. The standard deviations could not be determined because the original data were not available. The values for the 1984 and 1990 sampling dates are means with standard deviations of four replicate field samples.

The soil profile was divided into five layers. Since most measurements were made at a 20-cm soil depth, this was set as the depth of the first soil layer for the simulations. The other four layers were determined based on the Plano soil data retrieved from SSURGO databases. The soil layer properties including D_b, depth, soil water content at wilting point and field capacity, percent sand and silt, pH, and organic C concentration were initialized based on the measured values in 1958 and the reported values from the soil database (Table 4). The first soil layer was initialized with 0.01 Mg ha^{-1} of crop residues. One hundred years of cultivation before the simulation was assumed to stabilize the SOM pools. The fractions of SOC in the biomass pool and humus in the passive pool were estimated by the model. Although EPIC is specially suited to estimate the impact of erosion on the soil C balance, these simulations do not include erosion simulation due to the relative flat terrain where the experimental plots are located.

Table 3. Soil properties of the experimental site in 1958, 1984, and 1990, with standard errors in parentheses.

			Soil organic			Microbial biomass	
Date	Treatment†	Depth	C	N	pH	C	N
		cm	g kg^{-1}			mg kg^{-1}	
1958	all	0–15	18.8	NA	6.8	NA	NA
1984	LTN1	0–15	19.6 (0.6)	1.56 (0.08)	6.1 (0.2)	NA	NA
	LTN2	0–15	22.0 (1.5)	1.74 (0.12)	5.5 (0.1)	NA	NA
	LTN3	0–15	22.2 (0.9)	1.81 (0.07)	5.0 (0.1)	NA	NA
1990	LTN1-N0	0–20	19.2 (0.1)	1.47 (0.03)	6.2 (0.3)	164 (15)	23 (1)
	LTN2-N0	0–20	20.9 (0.7)	1.63 (0.05)	5.9 (0.4)	163 (30)	23 (2)
	LTN3-N0	0–20	22.1 (1.5)	1.71 (0.13)	5.4 (0.1)	174 (33)	24 (2)
	LTN2-N84	0–20	22.9 (2.0)	1.74 (0.17)	5.5 (0.3)	168 (7)	23 (0)
	LTN3-N168	0–20	21.5 (1.0)	1.84 (0.13)	5.1 (0.1)	140 (28)	26 (2)

† See Table 1 for treatment details.

Field Management

The 34-yr fertilization, tillage, and crop planting and harvesting information were grouped together to create a field operations input file for each of the five selected N treatments: LTN1-N0, LTN2-N0, LTN3-N0, LTN2-N84, and LTN3-N168. The five treatments had the same tillage operations as well as planting and harvesting dates.

Potential heat units were estimated as 1640°C using the average of 34-yr growing degree days (GDD) accumulation during the normal growing season. The average start and end date of the normal growing season was determined as 11 May and 16 October, respectively, by averaging the 34 yr of planting and harvest dates.

Model Calibration and Evaluation

Several parameters were identified to be sensitive to the model calculations of the yield and SOC and N. Three parameters are critical to the calculations of yield: biomass energy ratio (WA), harvest index (HI), and minimum harvest index (WSYF). Biomass energy ratio is used in the model for converting energy to biomass and its value for corn was adjusted to 35 kg ha^{-1} MJ^{-1} m^2 according to the WA range summarized by Sinclair and Muchow (1999). Harvest index is defined as the ratio between crop yield and above ground biomass. The final HI used for the yield calculation in the model is adjusted based on heat unit index (HUI), percent growing season, and fraction harvest index. Harvest index is the main determinant of yield when the adjusted HI is larger than WSYF; otherwise, yield is determined by WSYF. The HI was calculated using observed data (range: 0.24–0.58) with the mean value of 0.41 used for HI and the minimum value of 0.24 for WSYF.

The residue-decay tillage coefficient is an exponential coefficient expressing the tillage effect on residue decay rate and

Table 4. Initial soil input parameters.

		Soil layer				
	Unit	1	2	3	4	5
Layer depth	m	0.2	0.36	1.24	1.52	1.83
Bulk density	Mg m^{-3}	1.47	1.49	1.49	1.55	1.53
Wilting point	m m^{-1}	0.18	0.18	0.21	0.14	0.09
Field capacity	m m^{-1}	0.33	0.33	0.35	0.3	0.27
Sand	%	9	9	6	33	14
Silt	%	68	68	64	44	71
Organic N	g Mg^{-1}	1692	1530	315	153	153
pH		6.8	6.8	6.2	6.45	7
Organic C	%	1.88	1.7	0.35	0.17	0.17

is very sensitive to soil C and N dynamics. A small value for the decay coefficient results in higher accumulation of SOC and N. The coefficient was set to a value of 6.0. The value of the C to N ratio, used by the model to estimate the initial soil organic N based on the initial SOC, was set to 11 according to the measured soil C and N data in 1984 and 1990.

The EPIC model was evaluated for its accuracy in simulating corn yield and SOC and N. Simulation error [(simulated − observed)/observed] was used to indicate the difference in mean values and is expressed as a percentage. Root mean squared error (RMSE) and its percentage of the observed data (RMSE%; RMSE/observed mean) were used to evaluate the simulation errors in each year. The measured yield means were regressed against simulated values to test if slopes and intercepts were significantly different from 1.0 and 0.0, respectively.

RESULTS AND DISCUSSION

Corn Yield

Corn yields of five N fertilizer treatments (LTN1, LTN2-N0, LTN2-N84, LTN3-N0, and LTN3-N168) were simulated with EPIC during 1958–1991. Since the observed corn yields were not available for the 5-yr period of 1963–1967, 29 yr of simulated and observed yields were compared for 1958–1962 and 1968–1991. Observed yields were converted to dry grain yields (0% moisture) to compare against the simulated values.

During the long-term N treatment period from 1958 to 1983, the simulated yield means agree well with the observed means resulting in simulation errors from 1 to −5% (Table 5). Agreement between simulated and observed yields decreased during the short-term N residual effect period of 1984–1991 as evidenced by the spread of simulation errors (−42 to 12%). EPIC did not capture the average changes in yield experienced when the fertilization regime changed in 1984. In their uncertainty analysis of EPIC using the same data set, Wang et al. (2005) utilized a total of 1500 parameter sets (different combinations of yield and SOC related parameters) to simulate a range of corn yields (3.3–6.4 Mg ha^{-1}; observed = 0.977 × simulated + 0.068; R^2 = 0.996, $p <$ 0.001) that agreed well with observations.

Table 5. Observed and simulated yield means, error, and root mean square error (RMSE).

Treatment†	Observed	Simulated	RMSE	RMSE	Error
	Mg ha^{-1}			%	
		1958–1983			
LTN1	3.19 ± 1.29	3.03	1.48	46.4	−5.0
LTN2	5.80 ± 1.27	6.01	1.23	21.1	3.5
LTN3	6.08 ± 1.32	6.15	1.43	23.5	1.0
		1984–1991			
LTN1-N0	3.68 ± 0.42	2.13	1.66	45.1	−41.9
LTN2-N0	5.06 ± 0.81	4.02	1.45	28.6	−20.6
LTN3-N0	5.43 ± 1.44	6.11	1.39	25.7	12.5
LTN2-N84	7.70 ± 1.07	5.85	2.38	30.9	−24.0
LTN3-N168	7.75 ± 1.44	6.15	2.29	29.5	−20.7
		1958–1991			
LTN1-N0	3.33 ± 1.13	2.79	1.53	46.1	−16.3
LTN2-N0	5.60 ± 1.20	5.46	1.29	23.1	−2.5
LTN3-N0	5.90 ± 1.36	6.14	1.42	24.0	3.9
LTN2-N84	6.33 ± 1.48	5.96	1.63	25.7	−5.7
LTN3-N168	6.54 ± 1.53	6.15	1.71	26.1	−6.1

† See Table 1 for treatment details.

In LTN1, from the first simulation period to the second EPIC predicted a 10% reduction in yield while the observed yields actually increased by 5%. On average, this 8-yr period was 0.7°C warmer and 6% wetter than the first period, which explains the slight increase in observed yield. Conversely, the 10% decrease simulated by EPIC occurred because of a decrease in water stress and increases in N and temperature stresses. Further discussion is provided in the Crop Stress and Net Nitrogen Mineralization (NMN) sections, below. For the other treatments, the percent yield change simulated by EPIC was less than the observed.

The annual results of the simulated and observed yields for different N treatments are illustrated in Fig. 2.

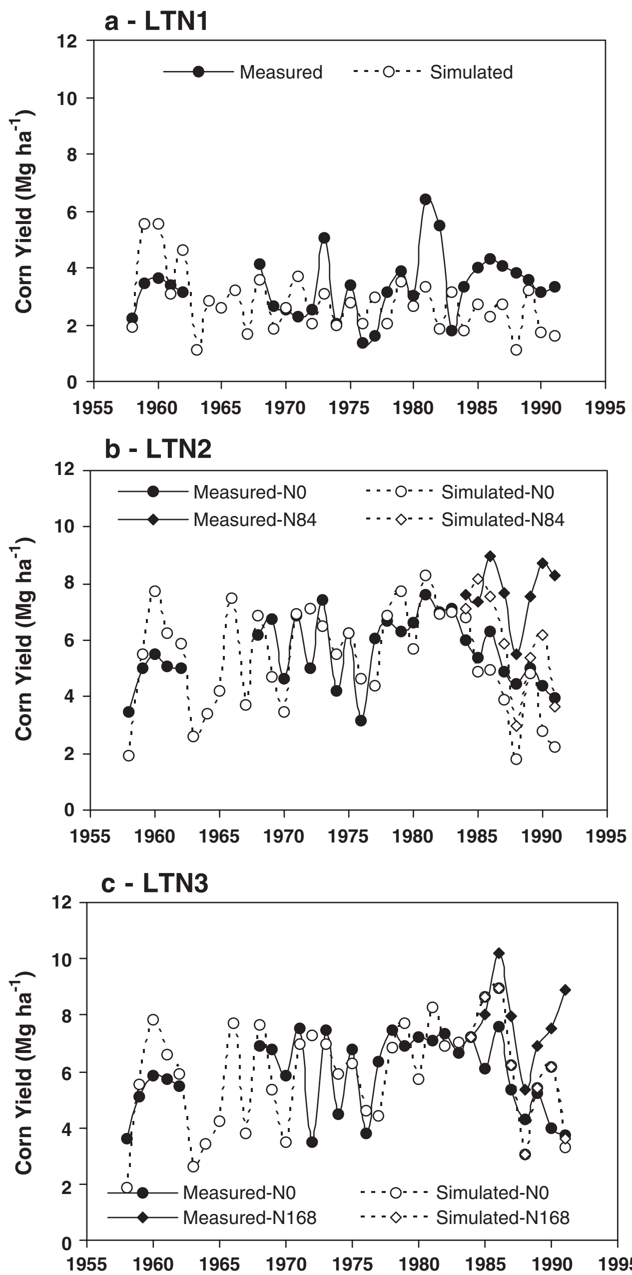

Fig. 2. Observed and simulated corn yields as affected by long-term N applications.

In general, the model captured the N effects on, and the annual variability of, corn yields. Simulated and observed mean yields during 1958–1991 were highly correlated ($R^2 = 0.961$, $p < 0.01$). Before 1984, the medium (LTN2) and high (LTN3) N rate plots exhibited similar yields while the control plot (LTN0) produced corn yields lower than LTN2 and LTN3. The simulated annual yields do not agree with the observed values for all the N treatments, but the simulations for the two fertilized plots display better agreement than those for the control plot. From 1958 to 1961, simulated yields were greater than observed yields. The simulated yields in 1972, 1974, and 1977 do not agree well with the observed values for the two N treated plots, possibly because of the simulation of crop stresses. In 1972, the observed corn yields were 5.0 and 3.5 Mg ha^{-1}, respectively, for the medium and high N rate plots. The control plot had extremely high yields of 5.07 in 1973 and 6.42 Mg ha^{-1} in 1981. We lack technical reasons to explain these observations or attribute these unexpected results to human error. After 1984, simulated yields on all five treatments were considerably lower than observed yields, with the largest difference of 5.25 Mg ha^{-1} occurring in the LTN3-N168 treatment in 1991 (Fig. 2c). One possible reason may be the gradual implementation of improved agronomic practices (e.g., corn hybrids, soil tilth, and cultural practices), which translated into improved observed yields (Vanotti and Bundy, 1996) but not simulated yields. Another explanation could be in how the model simulates the rate of production of N available for plant uptake. This hypothesis will be further explored in the Net Nitrogen Mineralization (NMN) section, below.

Crop Stress

On average, the total annual number of stress days (water + N + temperature) simulated by EPIC during 1958–1991 was 75.8 for LTN1, 45.2 for LTN2-N0, 38.5 for LTN2-N84, 40.6 for LTN3-N0, and 38.3 for LTN3-N168. The level of N application was a major factor influencing the total number of stress days "experienced" by the simulated corn crops. Total stress in the LTN1-N0 plot was always greater than in the fertilized plots, even after 1983 when N application was terminated or reduced (3a, 3b, 3c, 3d, 3e). These higher levels of stress help explain the low yields in the simulated crops (Fig. 2a). The difference in stress days simulated between the fertilized plots before 1984 is small, while after 1983 LTN2-N0 (Fig. 3b) shows significantly higher stress than the other three fertilized subplots (Fig. 3c, 3d, 3e). The small differences in stress between fertilized treatments before 1984 imply that the medium N rate provided sufficient N to satisfy crop needs, which is consistent with the similar yields obtained during the period (Table 5).

From 1984 onward, LTN2-N0 experienced greater stress than LTN3-N0 (Fig. 3b, 3d), which suggests that the medium N rate plot did not have as much residual N as the high N rate plot and that the soil N pool could not mineralize N in the quantities required by the crop (see Net Nitrogen Mineralization (NMN) section, below). The remaining three fertilized subplots (Fig. 3c, 3d, 3e), LTN2-N84, LTN3-N0, and LTN3-N168, display little difference in stress after 1983 and, consequently, little difference in their simulated yields. The large differences among observed yields of fertilized plots after 1983 partly explain the large simulation errors in yield estimation (Table 5). This might be caused by EPIC either underestimating residual N effects or overestimating crop N needs. Water stress was a major factor affecting crop growth and yield on the fertilized plots (Fig. 3b, 3c, 3d, 3e). The temperature stress caused by temperature extremes represented a small fraction of the total number of stress days simulated for the various treatments (Fig. 3a, 3b, 3c, 3d, 3e).

Soil Organic Matter Dynamics and Bulk Density

The simulated and observed values of SOC, N, and C to N ratio in 1984 and 1990 for the top 20-cm soil profile are presented in Table 6 and Fig. 4. The observed amounts of C accumulation in the soil were directly proportional to N application rate. The C increase occurred because of the return of corn residues to the soil after harvest and the low levels of initial SOM, a result of prior management practices that reduced soil C levels, such as burning and multiple tillage events (Vanotti et al., 1997). The simulated C values agree well with the observed values, with errors ranging from −5.8 to 0.5%. Before 1985, simulated SOC increased in the two fertilized plots while in the control plot SOC increased during the first 3 yr but declined in 1984 (Fig. 4a). The model fails in simulating the SOC increase in the control plot, probably because it underestimates the capacity of the soil to transform the corn residues into SOM. The observed SOC in 1990 decreased for all the treatments except LTN2-N84. The simulation errors of SOC in 1990 ranged from −5.1 to 0.7%. The large variations within simulated soil C since 1985 can be explained by the large variations in precipitation and the sudden reduction in N application, which requires time for soil to reach a new stabilized state.

The N simulation errors ranged from −0.7 to 2.9% in 1984 and from −1.6 to 5.9% in 1990 (Table 6). All treatments display a decrease in simulated soil organic N in the first year, followed by steady increases in the fertilized plots but a continued decrease in the control plot (Fig. 4b). Since 1984, the soil N tends to stabilize in all the plots except LTN2-N0, which shows a small decrease in N.

The C to N ratio increases suddenly in the first 4 yr, then becomes stable after 12 yr (Fig. 4c). Starting in 1984, the C to N ratio starts to fluctuate along with SOC. The simulation errors of C to N ratio are from −6.3 to −1.2% in 1984 and from −10.2 to 2.4% in 1990.

Figure 5 illustrates the annual change of the simulated D_b within the top 20-cm soil depth. The initial D_b is 1.47 Mg m^{-3}. The fertilized treatments showed declining D_b during the experiment while the control treatment showed the reverse. In 1983, the D_b in fertilized plots and the control plot were 1.45 and 1.49 Mg m^{-3}, respectively. Large variations in D_b during the residual effect period (1984–1991) correspond to the variations in SOC.

Soil Carbon Sequestration Rates

A major reason for developing soil carbon or agroecosystem models is to be able to use them to predict

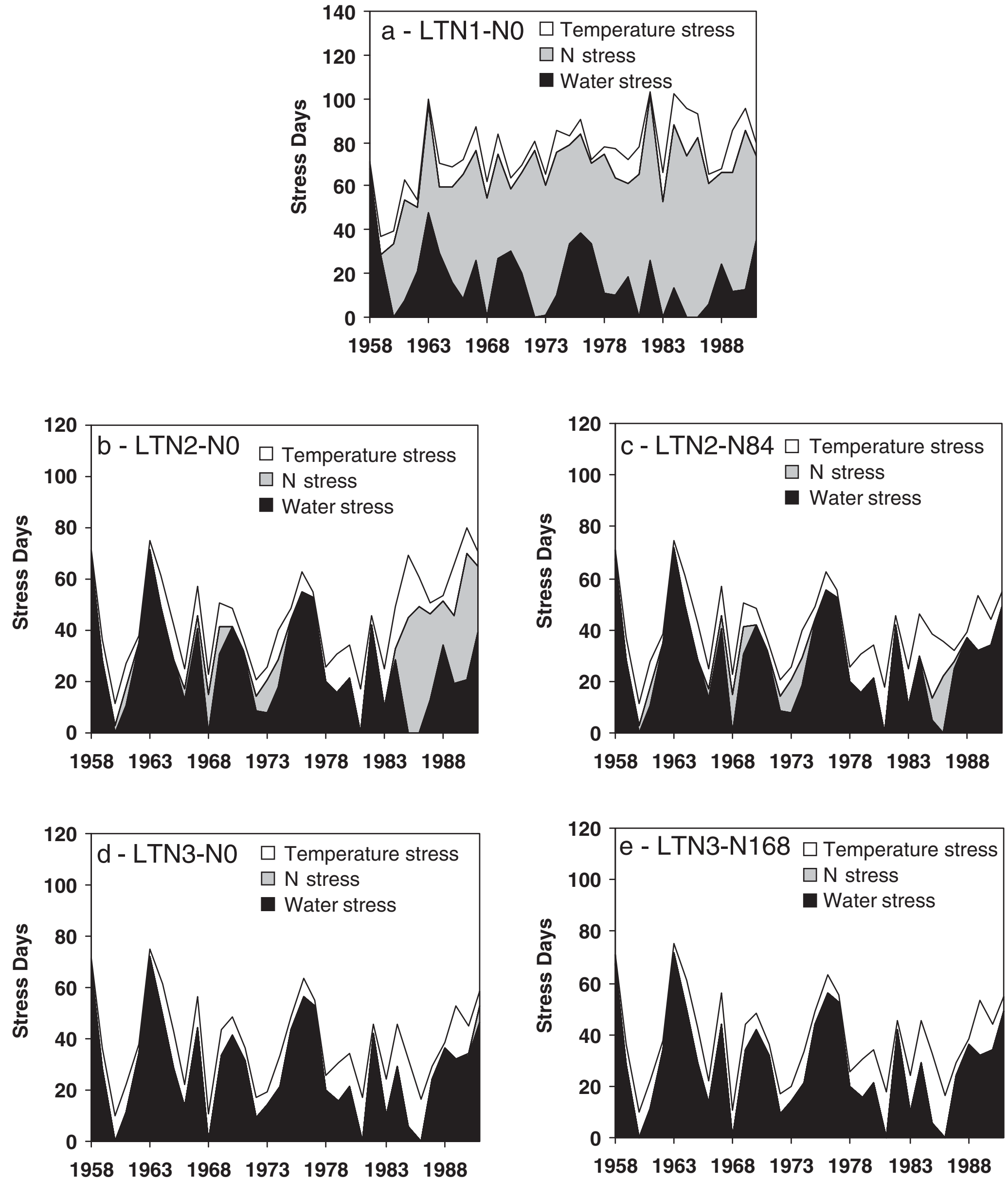

Fig. 3. Annual number of water, N, and temperature stress days by treatment.

SOC changes under climate–soil management combinations lacking soil C measurements. We tested this premise by comparing the observed and simulated long-term effects of N fertilization on SOC change (ΔSOC) for the periods of 1958–1984 and 1958–1990 (Fig. 6). The quadratic equations fitted to the observed and simulated data resemble typical crop yield responses to fertilizer application suggesting there is an optimum N addition for SCS. Similar response curves were obtained by Solberg et al. (1998) in central Alberta, Canada, for SOC and light fraction C. The EPIC model captured the magnitude of SCS for the two periods under consideration although for the LTN1-N0 treatment it predicted small annual SOC losses instead of the observed SOC gains.

We used the quadratic regression equations in Fig. 6 to determine the level of fertilizer N added leading to maximum SCS rate. These were 172 ± 20 kg N ha^{-1} yr^{-1} for the observed data and 163 ± 8 kg N ha^{-1} yr^{-1} for the simulations. These values suggest that the model is able to reproduce SCS rates observed in the field experiment during the simulation period.

Soil Microbial Biomass Carbon and Nitrogen

In their study of the long-term impacts of N fertilization on corn productivity and soil organic matter dynamics, Vanotti et al. (1997) evaluated the status of microbial biomass C and N in surface soil samples taken in 1990. Observed microbial biomass C ranged from 140 to 174 mg kg^{-1} soil while biomass N ranged from 23 to 26 mg kg^{-1} (Table 7). No clear trend was detected in measured microbial biomass C and N concentrations as a function of N treatment. Simulated microbial biomass C and N doubled or even tripled their values as N level

Table 6. Simulated and observed soil organic carbon (SOC), soil organic nitrogen (SON), and C to N ratio.

Treatment†	Measured 1984	Measured 1990	Simulated 1984	Simulated 1990	Error 1984	Error 1990
					%	
			SOC, g kg^{-1}			
LTN1-N0	19.6	19.2	18.5	18.2	−5.8	−5.1
LTN2-N0	22.0	20.9	22.1	20.9	0.5	−0.1
LTN3-N0	22.2	22.1	21.8	22.1	−1.9	0.1
LTN2-N84	22.0	22.9	22.1	22.2	0.4	−3.0
LTN3-N168	22.2	21.5	21.8	21.7	−1.9	0.7
			SON, g kg^{-1}			
LTN1-N0	1.56	1.47	1.567	1.552	0.5	5.6
LTN2-N0	1.73	1.63	1.768	1.727	2.2	5.9
LTN3-N0	1.81	1.71	1.797	1.786	−0.7	4.4
LTN2-N84	1.73	1.74	1.781	1.788	2.9	2.7
LTN3-N168	1.81	1.84	1.801	1.811	−0.5	−1.6
			C to N ratio			
LTN1-N0	12.56	13.06	11.78	11.73	−6.3	−10.2
LTN2-N0	12.72	12.82	12.51	12.09	−1.6	−5.7
LTN3-N0	12.27	12.92	12.12	12.39	−1.2	−4.1
LTN2-N84	12.72	13.16	12.41	12.42	−2.5	−5.6
LTN3-N168	12.27	11.68	12.09	11.96	−1.4	2.4

† See Table 1 for treatment details.

increased from lowest to highest (Table 7). There was no correlation between observed and simulated values of microbial biomass C ($r = 0.139$); however, there was a positive correlation between observed and simulated microbial biomass N ($r = 0.793$, significant at the 0.05 probability level). The observed C to N ratio of microbial biomass averaged approximately 7 while the simulated ratio averaged approximately 10. On average, the simulated proportion of SOC represented by the microbial biomass was 1.8% while the observed was 0.8%. A closer agreement was obtained by Izaurralde et al. (2006) using the same version of EPIC when simulating microbial biomass C levels (2.4%) and comparing them to measurements (2.6%) from a long-term experiment at Breton, Canada.

Net Nitrogen Mineralization (NMN)

To evaluate the model's ability to simulate NMN, we used EPIC to emulate a leaching–incubation experiment conducted by Vanotti et al. (1997) during a 280-d period. In this experiment, fresh soil samples taken in 1990 were incubated during 280 d at 35°C and 85 kPa of soil water potential following the procedure of Stanford and Smith (1972). We prepared a set of input files to approximate the conditions under which the N mineralization data had been obtained. The daily maximum and minimum temperatures were maintained between 36 and 34°C throughout the simulation. Precipitation was set to zero while the automatic irrigation option was turned on each time the soil water potential reached 85 kPa. The soil output files in 1989 were used as input files for the 1990 simulations. The lab-determined cumulative NMN ranged from 87 mg N kg^{-1} (LTN1-N0) to 125 mg N kg^{-1} (LTN3-N168) (Table 8). The simulated NMN values followed the pattern of those from the laboratory incubations but were an order of magnitude smaller (Table 8). Cabrera and Kissel (1988a) used the Stanford and Smith procedure to predict NMN under

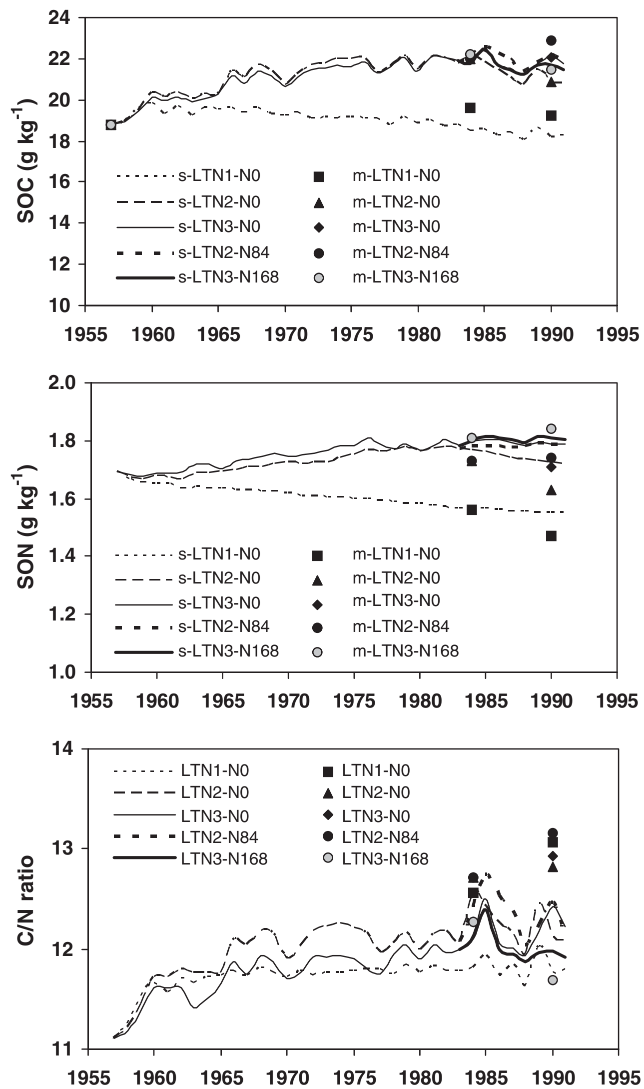

Fig. 4. Simulated and measured soil organic carbon (SOC), soil organic nitrogen (SON), and C to N ratio in top 20-cm soil. Lines represent simulated values while symbols represent measured values.

field conditions and found that, on average, the NMN values determined during two growing seasons in three Kansas soils were one third those predicted with the lab technique. For comparison, the EPIC simulated NMN values represented 8% of the lab-determined NMN values. Cabrera and Kissel (1988a) attributed the discrepancies between field and laboratory determinations to inadequate adjustments in the soil water content factor to calculate N mineralization and the use of disturbed soil samples in the lab incubation. While the former explanation is not a factor in our case, the use of disturbed soil samples in the lab incubation conducted by Vanotti et al. (1997) may have contributed to enhance NMN due to drying, rewetting, and disrupting of soil aggregates (Cabrera and Kissel, 1988a). In a comparison of methods to estimate potentially mineralizable N, Cabrera and Kissel (1988b) found that the use of disturbed soil samples always produced larger N mineralization than when using undisturbed soil samples. While

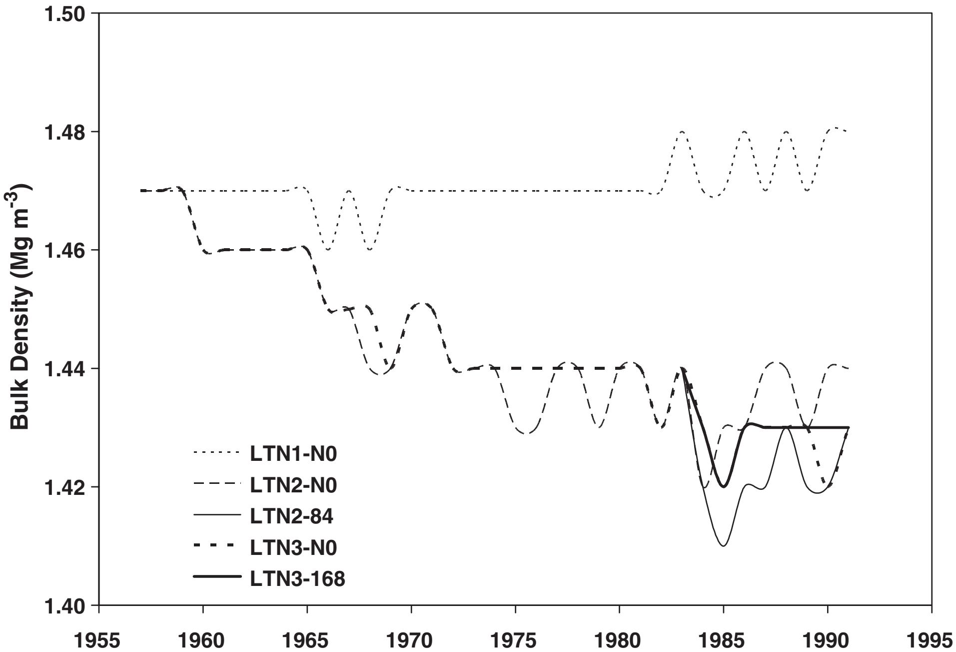

Fig. 5. Temporal dynamics of soil bulk density under different N treatments.

we do not rule out the possibility that N mineralization algorithms in EPIC may underpredict NMN observable under field conditions, we also hypothesize that methodological aspects of the lab incubation procedure precluded us from reaching a closer agreement between simulated and observed NMN.

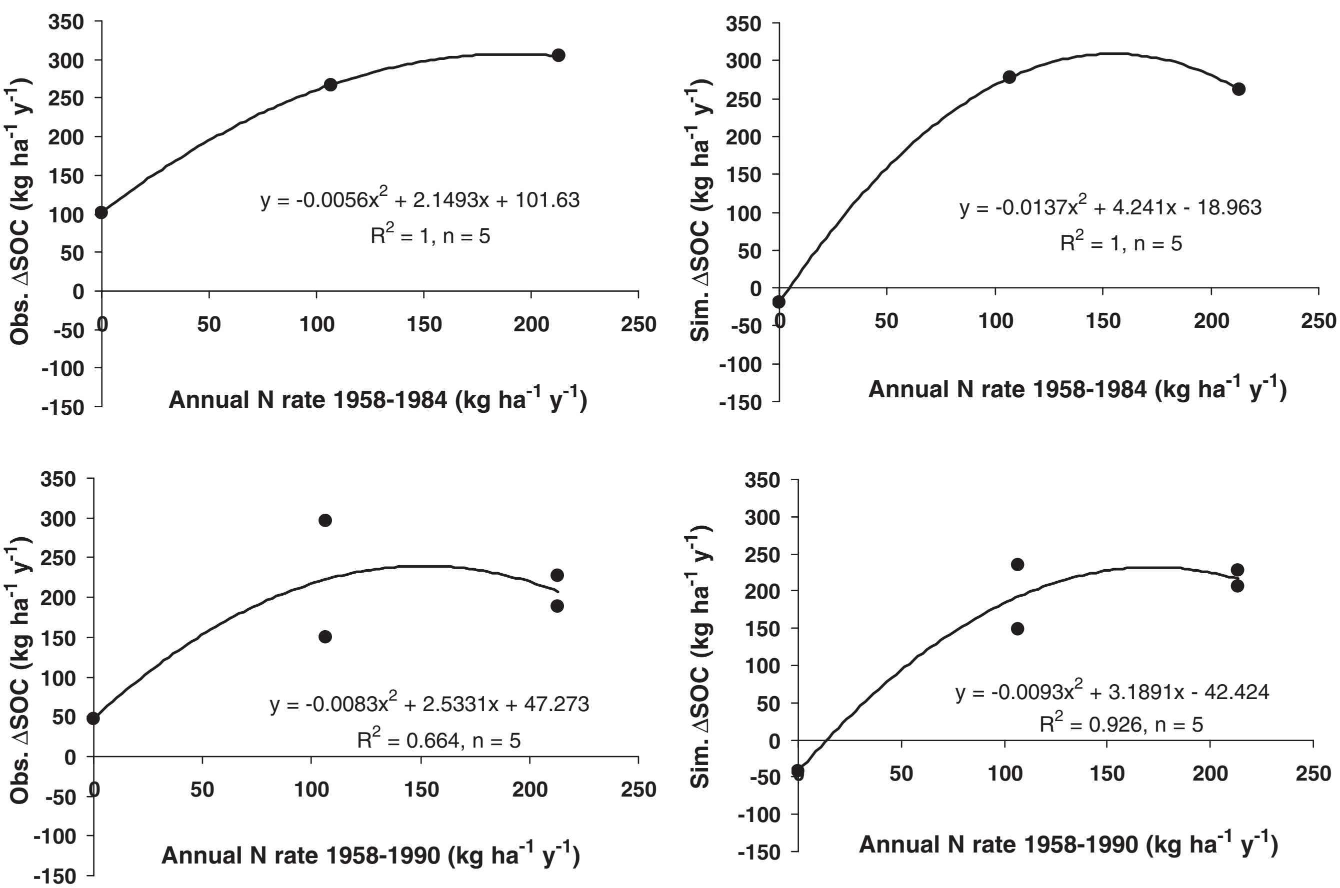

Fig. 6. Observed and simulated long-term effects of N fertilization on soil organic carbon change (ΔSOC) under continuous corn at Arlington, WI. Upper two figures are observed and simulated ΔSOC for 1958–1984. Lower two are for observed and simulated ΔSOC for 1958–1990.

Table 7. Simulated and observed soil microbial biomass C and N in 1990 at Arlington, WI.

Treatment†	Carbon		Nitrogen		C to N ratio	
	Simulated	Observed	Simulated	Observed	Simulated	Observed
	mg kg^{-1}					
LTN1-N0	190	164	16	23	11.7	7.1
LTN2-N0	312	163	27	23	11.4	7.1
LTN3-N0	447	174	41	24	10.8	7.3
LTN2-N84	452	168	42	23	10.8	7.3
LTN3-N168	454	140	56	26	8.1	5.4

† See Table 1 for treatment details.

Table 8. Simulated and laboratory-determined cumulative net nitrogen mineralization (NMN) in 0- to 20-cm samples of a Plano silt loam over a 280-d period.

Treatment†	Simulated D_b‡	Simulated NMN		Lab-determined NMN
	Mg m^{-3}	— kg N ha^{-1} —		mg N kg^{-1}
LTN1-N0	1.48	14	4.7	87.0
LTN2-N0	1.46	19	6.5	95.0
LTN3-N0	1.45	22	7.6	120.0
LTN2-N84	1.45	25	8.6	116.0
LTN3-N168	1.44	54	18.8	125.0

† See Table 1 for treatment details.
‡ Bulk density.

CONCLUSIONS

In this study we evaluated the EPIC model by comparing simulations of the long-term dynamics of corn yields and SOC with a 34-yr experiment from Arlington, Wisconsin. The model accurately simulated the effects of different N application rates on the corn yields as indicated by relatively low simulation errors averaging 9.7%, with an average RMSE of 1.62 Mg ha^{-1}. For the short-term N residual effect period, the errors and RMSE are higher. Overall, there was a high correlation between simulated and observed mean yields during 1958–1991 ($R^2 = 0.961$, $p < 0.01$).

The simulation error in SOC was similar in 1984 and 1990. The model failed in simulating the SOC increase in the control plot, most likely because it underestimated the capacity of the soil to transform the residues into SOM. The errors in N simulation and in the C to N ratio simulation were greater in 1990 than in 1984, reflecting a change in experimental fertilizer applications. This shows that the response time of the model to these changes was longer than the response time of the experimental plots.

Overall, our results suggest that the EPIC model adequately simulated average crop yields but did not fully capture their annual variability, a finding that is consistent with those of Williams et al. (1989), Kiniry et al. (1995), and Roloff et al. (1998a, 1998b, 1998c). Our results also show realistic depictions of SOC dynamics, accurate estimations of SCS rates, but a less-than-ideal microbial biomass component. Simulations of net N mineralization rates were realistic but the predicted values turned out to be lower than those determined from leaching–incubation experiments of disturbed soil samples. Opportunities exist for improvements in the microbial biomass component, the model in N cycling component, the crop residual N effect, and the soil response time to changing input conditions.

ACKNOWLEDGMENTS

Research conducted within the CASMGS (Consortium for Agricultural Soils Mitigation of Greenhouse Gases) and CSiTE (Consortium for Research on Enhanced Carbon Sequestration in Terrestrial Ecosystems) programs. CASMGS is supported by the USDA and USEPA. CSiTE is supported by the U.S. Department of Energy, Office of Science, as part of the Terrestrial Carbon Sequestration program in the Office of Biological & Environmental Research.

REFERENCES

Adams, W.A. 1973. The effect of organic matter on the bulk and true densities of some uncultivated podzolic soils. J. Soil Sci. 24:10–17.

Allmaras, R.R., H.H. Schomberg, C.L. Douglas, Jr., and T.H. Dao. 2000. Soil organic carbon sequestration potential of adopting conservation tillage in U.S. croplands. J. Soil Water Conserv. 55:365–373.

Bernardos, J.N., E.F. Viglizzo, V. Jouvet, F.A. Lertora, A.J. Pordomingo, and F.D. Cid. 2001. The use of EPIC model to study the agroecological change during 93 years of farming transformation in the Argentine pampas. Agric. Syst. 69:215–234.

Brown, R.A., and N.J. Rosenberg. 1997. Sensitivity of crop yield and water use to change in a range of climatic factors and CO2 concentrations: A simulation study applying EPIC to the central USA. Agric. For. Meteorol. 83:171–203.

Brown, R.A., and N.J. Rosenberg. 1999. Climate change impacts on the potential productivity of corn and winter wheat in their primary United States growing regions. Clim. Change 41:73–107.

Brown, R.A., N.J. Rosenberg, C.J. Hays, W.E. Easterling, and L.O. Mearns. 2000. Potential production and environmental effects of switchgrass and traditional crops under current and greenhouse-altered climate in the central United States: A simulation study. Agric. Ecosyst. Environ. 78:31–47.

Cabelguenne, M., C.A. Jones, J.R. Marty, P.T. Dyke, and J.R. Williams. 1990. Calibration and validation of EPIC for crop rotations in southern France. Agric. Syst. 33:153–171.

Cabrera, M.L., and D.E. Kissel. 1988a. Evaluation of a method to predict nitrogen mineralized from soil organic matter under field conditions. Soil Sci. Soc. Am. J. 52:1027–1031.

Cabrera, M.L., and D.E. Kissel. 1988b. Potentially mineralizable nitrogen in disturbed and undisturbed soil samples. Soil Sci. Soc. Am. J. 52:1010–1015.

Cavero, J., R.E. Plant, C. Shennan, D.B. Friedman, J.R. Williams, J.R. Kiniry, and V.W. Benson. 1999. Modeling nitrogen cycling in tomato-safflower and tomato-wheat rotations. Agric. Syst. 60:123–135.

Chung, S.W., P.W. Gasman, D.R. Huggins, and G.W. Randall. 2001. EPIC tile flow and nitrate loss predictions for three Minnesota cropping system. J. Environ. Qual. 30:822–830.

Cole, V., C. Cerri, K. Minami, A. Mosier, N. Rosenberg, and D. Sauerbeck. 1996. Agricultural options for mitigation of greenhouse gas emissions. p. 744–771. *In* R.T. Watson et al. (ed.) Climate Change 1995: Impacts, adaptations and mitigation of climate change. Cambridge Univ. Press, Cambridge.

Costantini, E.A.C., F. Castelli, S. Raimondi, and P. Lorenzoni. 2002. Assessing soil moisture regimes with traditional and new methods. Soil Sci. Soc. Am. J. 66:1889–1896.

Dhakhwa, G., C.L. Campbell, S.K. LeDuc, and E.J. Cooter. 1997. Maize growth: Assessing the effects of global warming and CO2 fertilization with crop models. Agric. For. Meteorol. 87:253–272.

Easterling, W.E., X.F. Chen, C. Hays, J.R. Brandle, and H.H. Zhang. 1996. Improving the validation of model-simulated crop yield response to climate change: An application to the EPIC model. Clim. Res. 6:263–273.

Favis-Mortlock, D.T., R. Evans, J. Boardman, and T.M. Harris. 1991. Climate change, winter wheat yield and soil erosion on the English South Downs. Agric. Syst. 37:415–433.

Hughes, D., W. Butcher, A. Jaradat, and W. Penaranda. 1995. Economic analysis of the long-term consequences of farming practices in the barley cropping area of Jordan. Agric. Syst. 47:39–58.

Intergovernmental Panel on Climate Change. 2001. Climate Change 2001: The scientific basis. Cambridge Univ. Press, Cambridge.

Izaurralde, R.C., K.H. Haugen-Kozyra, D.C. Jans, W.B. McGill, R.F. Grant, and J.C. Hiley. 2001a. Soil C dynamics: Measurement, simulation and site-to-region scale-up. p. 553–575. *In* R. Lal et al. (ed.) Assessment methods for soil carbon. Lewis Publ., Boca Raton, FL.

Izaurralde, R.C., N.J. Rosenberg, R.A. Brown, and A.M. Thomson. 2003. Integrated assessment of Hadley Centre (HadCM2) climate change projections on agricultural productivity and irrigation water supply in the conterminous United States—I. Regional agricultural production in 2030 and 2095. Agric. For. Meteorol. 117:97–122.

Izaurralde, R.C., N.J. Rosenberg, and R. Lal. 2001b. Mitigation of climatic change by soil carbon sequestration: Issues of science, monitoring, and degraded lands. Adv. Agron. 70:1–75.

Izaurralde, R.C., J.R. Williams, W.B. McGill, N.J. Rosenberg, and M.C. Quiroga Jakas. 2006. Simulating soil C dynamics with EPIC: Model description and testing against long-term data. Ecol. Modell. 192: 362–384.

Janzen, H.H., C.A. Campbell, R.C. Izaurralde, B.H. Ellert, N. Juma, W.B. McGill, and R.P. Zentner. 1998. Management effects on soil C storage on the Canadian prairies. Soil Tillage Res. 47:181–195.

Jenkinson, D.S., and D.S. Powlson. 1976. The effects of biocidal treatments on metabolism in soil. V. A method for measuring soil biomass. Soil Biol. Biochem. 8:209–213.

Keeling, C.D., and T.P. Whorf. 2004. Atmospheric CO2 concentrations (ppmv) derived from in situ air samples collected at Mauna Loa Observatory, Hawaii. Available at http://cdiac.esd.ornl.gov/ftp/maunaloa-co2/maunaloa.co2 (verified 2 Mar. 2006). Oak Ridge Natl. Lab., Oak Ridge, TN.

Kelly, T.C., Y. Lu, and J. Teasdale. 1996. Economic-environmental tradeoffs among alternative crop rotations. Agric. Ecosyst. Environ. 60:17–28.

Kiniry, J.R., D.J. Major, R.C. Izaurralde, J.R. Williams, P.W. Gassman, M. Morrison, R. Bergantine, and R.P. Zentner. 1995. EPIC model parameters for cereal, oilseed, and forage crops in the northern Great Plains region. Can. J. Plant Sci. 75:679–688.

Kucharik, C.J., K.R. Brye, J.M. Norman, J.A. Foley, S.T. Gower, and L.G. Bundy. 2001. Measurements and modeling of carbon and nitrogen cycling in agroecosystems of southern Wisconsin: Potential for SOC sequestration during the next 50 years. Ecosystems 4:237–258.

Lal, R., R.F. Follett, J.M. Kimble, and C.V. Cole. 1999. Managing U.S. cropland to sequester carbon in soil. J. Soil Water Conserv. 54:374–381.

Lee, J.J., D.L. Phillips, and R.F. Dodson. 1996. Sensitivity of the US corn belt to climate change and elevated CO2: II. Soil erosion and organic carbon. Agric. Syst. 52:503–521.

McKenney, M.S., W.E. Easterling, and N.J. Rosenberg. 1992. Simulation of crop productivity and responses to climate change in the year 2030: The role of future technologies, adjustments and adaptations. Agric. For. Meteorol. 59:103–127.

Nelson, D.W., and L.E. Sommers. 1972. A simple digestion procedure for estimation of total nitrogen in soils and sediments. J. Environ. Qual. 1:423–425.

Parton, W.J., D.S. Ojima, C.V. Cole, and D.S. Schimel. 1994. A general model for soil organic matter dynamics: Sensitivity to litter chemistry, texture and management. p. 147–167. *In* Quantitative modeling of soil forming processes. SSSA Spec. Publ. 39. SSSA, Madison, WI.

Parton, W.J., D.S. Schimel, C.V. Cole, and D.S. Ojima. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Sci. Soc. Am. J. 51:1173–1179.

Parton, W.J., J.M.O. Scurlock, D.S. Ojima, T.G. Gilmanov, R.J. Scholes, D.S. Schimel, T. Kirchner, J.-C. Menaut, T. Seastedt, E. Garcia Moya, A. Kamnalrut, and J.I. Kinyamario. 1993. Observations and modelling of biomass and soil organic matter dynamics for the grassland biome worldwide. Global Biogeochem. Cycles 7:785–809.

Phillips, D.L., J.J. Lee, and R.F. Dodson. 1996. Sensitivity of the US Corn Belt to climate change and elevated CO_2: I. Corn and soybean yields. Agric. Syst. 52:481–502.

Pierson, S.T., M.L. Cabrera, G.K. Evanylo, P.D. Schroeder, D.E. Radcliffe, H.A. Kuykendall, V.W. Benson, J.R. Williams, C.S. Hoveland, and M.A. McCann. 2001. Phosphorus losses from grasslands fertilized with broiler litter: EPIC simulations. J. Environ. Qual. 30:1790–1795.

Post, W.M., R.C. Izaurralde, J.D. Jastrow, B.A. McCarl, J.E. Amonette, V.L. Bailey, P.M. Jardine, T.O. West, and J. Zhou. 2004. Carbon sequestration enhancement in U.S. soils. Bioscience 54:895–908.

Post, W.M., and K.C. Kwon. 2000. Soil carbon sequestration and land-use change: Processes and potential. Glob. Change Biol. 6: 317–327.

Poudel, D.D., D.J. Midmore, and L.T. West. 2000. Farmer participatory research to minimize soil erosion on steepland vegetable systems in the Philippines. Agric. Ecosyst. Environ. 79:113–127.

Rinaldi, M. 2001. Application of EPIC model for irrigation scheduling of sunflower in Southern Italy. Agric. Water Manage. 49:185–196.

Roloff, G., R. de Jong, C.A. Campbell, R.P. Zentner, and V.M. Benson. 1998a. EPIC estimates of soil water, nitrogen and carbon under semiarid temperate conditions. Can. J. Soil Sci. 78:551–562.

Roloff, G., R. de Jong, and M.C. Nolin. 1998b. Crop yield, soil temperature and sensitivity of EPIC under central-eastern Canadian conditions. Can. J. Soil Sci. 78:431–439.

Roloff, G., R. de Jong, R.P. Zentner, C.A. Campbell, and V.M. Benson. 1998c. Estimating spring wheat yield variability with EPIC. Can. J. Soil Sci. 78:541–549.

Sinclair, T.R., and R.C. Muchow. 1999. Radiation use efficiency. Adv. Agron. 65:215–265.

Smith, P., R. Milne, D.S. Powlson, J.U. Smith, P. Falloon, and K. Coleman. 2000. Revised estimates of the carbon mitigation potential of UK agricultural land. Soil Use Manage. 16:293–295.

Smith, P., J.U. Smith, D.S. Powlson, W.B. McGill, J.R.M. Arah, O.G. Chertov, K. Coleman, U. Franko, S. Frolking, D.S. Jenkinson, L.S. Jensen, R.H. Kelly, H. Klein-Gunnewiek, A. Komarov, C. Li, J.A.E. Molina, T. Mueller, W.J. Parton, J.H.M. Thornley, and A.P. Whitmore. 1997. A comparison of the performance of nine soil organic matter models using seven long-term experimental datasets. Geoderma 81:153–225.

Solberg, E.D., M. Nyborg, R.C. Izaurralde, S.S. Malhi, H.H. Janzen, and M. Molina-Ayala. 1998. Carbon storage in soils under continuous cereal grain cropping: N fertilizer and straw. p. 235–254. *In* R. Lal et al. (ed.) Management of carbon sequestration in soil. Advances in Soil Science. CRC Press, Boca Raton, FL.

Stanford, G., and S.J. Smith. 1972. Nitrogen mineralization potentials of soils. Soil Sci. Soc. Am. Proc. 36:465–472.

Stockle, C.O., P.T. Dyke, J.R. Williams, C.A. Jones, and N.J. Rosenberg. 1992b. A method for estimating the direct and climatic effects of rising atmospheric carbon dioxide on growth and yield of crops: Part II—Sensitivity analysis at three sites in the Midwestern USA. Agric. Syst. 38:239–256.

Stockle, C.O., J.R. Williams, N.J. Rosenberg, and C.A. Jones. 1992a. A method for estimating the direct and climatic effects of rising atmospheric carbon dioxide on growth and yield of crops: Part I—Modification of the EPIC model for climate change analysis. Agric. Syst. 38:225–238.

Tan, G., and R. Shibasaki. 2003. Global estimation of crop productivity and the impacts of global warming by GIS and EPIC integration. Ecol. Modell. 168:357–370.

Vanotti, M.B., and L.G. Bundy. 1996. Soil organic matter dynamics in the North American corn belt: The Arlington plots. p. 409–418. *In* D.S. Powlson et al. (ed.) Evaluation of soil organic matter models using existing long-term datasets. NATO ASI Ser. 38. Springer-Verlag, Berlin.

Vanotti, M.B., L.G. Bundy, and A.E. Peterson. 1997. Nitrogen fertilizer and legume-cereal rotation effects on soil productivity and organic matter dynamics in Wisconsin. p. 105–119. *In* E.A. Paul

et al. (ed.) Soil organic matter in temperate agroecosystems: Long-term experiments of North America. CRC Press, Boca Raton, FL.
Vitousek, P.M., D.R. Turner, W.J. Parton, and R.L. Sanford. 1994. Litter decomposition on the Mauna Loa environmental matrix, Hawaii: Patterns, mechanisms, and models. Ecology 75:418–429.
Wang, X., X. He, J.R. Williams, R.C. Izaurralde, and J.D. Atwood. 2005. Sensitivity and uncertainty analyses of crop productivity and soil organic carbon simulated with EPIC. Trans. ASAE 48:1041–1054.
Williams, J.R. 1995. The EPIC model. p. 909–1000. *In* V.P. Singh (ed.) Computer models of watershed hydrology. Water Res. Publ., Highlands Ranch, CO.
Williams, J.R., C.A. Jones, J.R. Kiniry, and D.A. Spanel. 1989. The EPIC crop growth-model. Trans. ASAE 32:497–511.
Yeomans, J.C., and J.M. Bremner. 1988. A rapid and precise method for routine determination of organic carbon in soil. Commun. Soil Sci. Plant Anal. 19:1467–1476.