Simulating Soil Carbon Dynamics, Erosion and Tillage with EPIC[1]

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ABSTRACT

Carbon sequestration in soil has emerged as a technology with significant potential to help stabilize atmospheric concentrations of greenhouse gases at non-threatening levels. Methods are thus needed to evaluate and recommend soil carbon sequestration practices based on their effects on carbon dynamics and environmental quality. There is scientific and practical consensus that simulation models will be integral to these methods. EPIC (Erosion Productivity Impact Calculator) is a widely used and tested model for simulating agroecosystem processes; it can handle multiple crops and has dynamic treatment of tillage, wind and water erosion, runoff, soil density, and leaching processes. In order to improve the simulation of soil carbon dynamics as affected by erosion and tillage, here we describe changes made to the EPIC model following concepts used in the Century model. The C and N dynamics captured from Century now interact directly with the soil moisture, temperature, erosion, tillage, soil density, leaching, and translocation functions of EPIC. Equations were also added to describe the role soil texture plays in soil organic matter stabilization. Differences in N mineralization and immobilization between the two models are explained. In the newly modified EPIC, leaching moves materials from surface litter to subsurface layers. In contrast to Century, the surface litter in EPIC has a slow but no passive compartment. Lignin concentration in EPIC is modeled as a sigmoidal function of plant age. Model comparisons against selected long-term data sets are presented and discussed.

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INTRODUCTION

Analyses of numerous field and simulation experiments have identified soil carbon sequestration (SCS) as a technology with significant potential to attenuate the rate of increase in atmospheric CO_2 (Cole et al., 1996; Lal et al., 1999; Allmaras et al., 2000; Smith et al., 2000). The technology is appealing because, were it to be deployed at global scales during the next decades, it could become part of a cost-effective emission-mitigation strategy aimed at stabilizing atmospheric CO_2 concentrations (Edmonds et al., 1999; Rosenberg et al., 1999). Therefore, comprehensive methods are needed to evaluate and recommend SCS practices that would have the desired effect not only on SCS but also on the preservation of environmental quality. Moreover, there is scientific and practical consensus that simulation models will be integral to these methods (Izaurralde et al., 1998).

It is well known that soil organic matter (SOM) is an essential attribute of soil quality (Doran et al., 1994). Many practices—some involving land use changes—have been shown to increase SOM and thus received considerable attention for their role in climate change mitigation (Janzen et al., 1998; Post and Kwon, 2000). No-tillage methods, for example, may increase the retention of atmospheric C in soil and reduce erosion rates, but may also alter the net balance of greenhouse gases such as N_2O which—per molecule—absorb more heat than CO_2 and thus contribute significantly to global warming. There is also uncertainty about the fate of C in eroded sediments. While deep burial of C in sediments, lakes, and oceans may lead to sequestration (Stallard, 1998), a fraction of eroded C redistributed over landscapes may also end up being emitted back to the atmosphere as CO_2 (Hardin et al., 1999; Lal, 1995).

The study of these complex relationships is best approached through model analyses of ecosystem processes in combination with experimental data and other databases. With support from the U.S. Department of Energy to the CSiTE (Carbon Sequestration in Terrestrial Ecosystems) Research Center, we are enhancing the capabilities of the EPIC model (Williams, 1995) with a new SOM module based on concepts used in the Century model (Parton et al., 1994) and a more detailed treatment about the production, consumption and flux of O_2, CO_2, N_2O and CH_4. The objectives of this paper are to a) describe components of the EPIC model as they relate to the C balance (e.g., tillage and erosion), b) explain modifications made to EPIC following concepts of C and N dynamics of the Century model, and c) present SOC results simulated with EPIC and compare these against data from two field experiments.

DESCRIPTION OF THE EPIC MODEL

EPIC (Williams et al., 1984) is a widely tested and adapted model originally built to quantify the effects of erosion on soil productivity. It has since evolved into a comprehensive agro-ecosystem model capable of describing the behavior of many crops grown in complex sequences and tillage operations (Williams, 1995). The model contains parameters to simulate about 100 crops and up to 12 plant species in a field. EPIC contains routines to handle CO_2 fertilization effects on plant growth and water use (Stockle et al., 1992a,b), hydrological balance, N and P cycling, soil density changes, tillage, erosion, and leaching (Fig. 1).

The tillage sub model in EPIC mixes nutrients and crop residues within the plow depth. It also simulates changes in bulk density, converts standing residue to flat residue, and determines ridge height and surface roughness. EPIC has subroutines to calculate wind and water erosion. Wind erosion is calculated on a daily time scale based on wind speed distribution and adjusted according to soil properties, surface roughness, vegetative cover, and distance across wind path. Water erosion is caused by the energy in rainfall and runoff. Six equations are available to the user. The Green and Ampt equation can be used to estimate infiltration during individual storms.

Special mention should be made of APEX (J.R. Williams, personal communication, 2000), a model based on EPIC, which is designed to simulate whole farm and small watershed management (up to 2500 km^2) including multiple fields, soil types, and landscape positions. In addition to containing all EPIC's functions, APEX has components that simulate routing of water, sediment, nutrients, and pesticides across complex landscapes and channel systems to the watershed outlet. Special routing mechanisms enable the evaluation of surface run-on and runoff, return flow, sediment deposition and degradation, nutrient transport, and groundwater flow as well as water quality as determined by N (ammonium, nitrate, and organic), P (soluble and adsorbed/mineral and organic) and pesticide concentrations. Although we will make no further reference to APEX in this paper, we anticipate that all the improvements in the C and N algorithms made to EPIC when transported into APEX will render a robust tool to investigate the complex relationships dominating soil C dynamics in eroding landscapes.

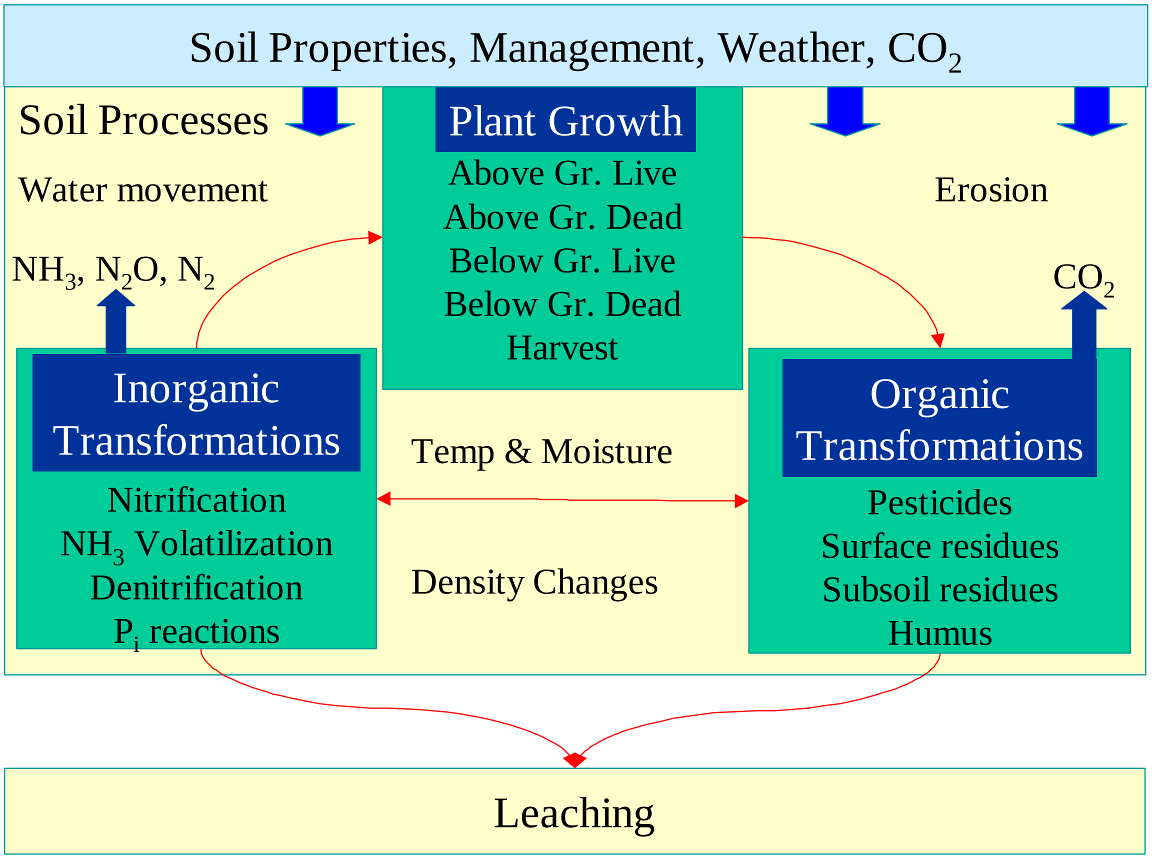

Fig. 1. Schematic diagram of interactions among diverse sub-models in EPIC.

DESCRIPTION OF CARBON AND NITROGEN ALGORITHMS INCORPORATED INTO THE EPIC MODEL

Concepts and equations from the Century model as described by Parton et al. (1987, 1993, and 1994) and Vitousek et al. (1994) were used to build a sub model in EPIC describing C and N transformations in soil and link these to the dynamic simulation of wind and water erosion. All equations were adapted to be executed on a daily time step. The flow diagram in Fig. 2 illustrates how the C added to soil as above or below ground plant residues and animal manures is partitioned into structural and metabolic C according to lignin and N contents. The C in structural and metabolic litter is subsequently distributed into the various kinetic compartments or evolved as CO_2.

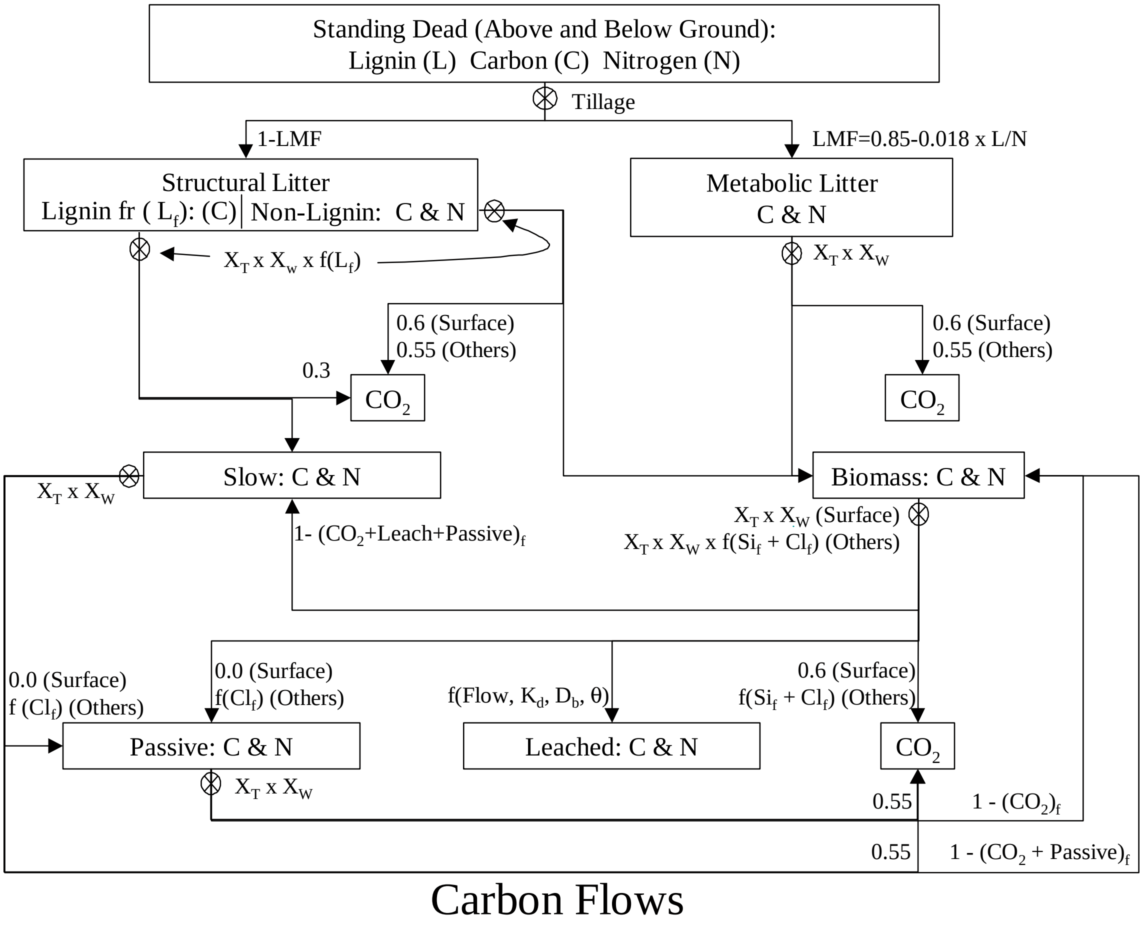

Fig 2. Modified C flows in EPIC. Numbers alone refer to fractions of C flow that go to CO_2. Symbols: XW and XT refer to moisture and temperature controls on soil biological processes; LMF = Fraction of the litter that is metabolic (kg kg^{-1}); L_f = fraction of structural litter that is lignin (kg kg^{-1}); lower case f = “function of”, and subscript $_f$ = “fraction”; Si_f = fraction of soil mineral component that is silt; Cl_f = fraction of soil mineral component that is clay; K_d = distribution coefficient of organic compounds between soil solid and liquid phases; D_b = soil bulk density; ? = soil volumetric water content. Flows that split are designated by double headed arrows.

As in Century, C and N compounds in EPIC are allocated into three compartments of increasing turnover time: biomass, slow and passive (Fig. 2). Carbon and N can also be leached or lost in gaseous forms. It was, however, neither required nor desired that all equations from one model be transported into the other. At least four major differences between the models regarding the organic transformations are worth mentioning here. Firstly, leaching equations currently in EPIC are used to move organic materials from surface litter to subsurface layers. Secondly, temperature and water controls affecting transformation rates are calculated with equations currently in EPIC. Thirdly, the surface litter fraction in EPIC has a slow but no passive compartment. Lastly, 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) (Fig. 2). 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/N ratio of the receiving compartment. If the N available exceeds the demand by all its receiving compartments, then the *potential* transformation 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 sub model 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 demands exceeds the total mineral N, then each net demand is met allowing each *potential* transformation to become the *actual* transformation. When the total N demand exceeds the mineral N available, then the sub model 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.

SIMULATION OF SOIL ORGANIC CARBON CHANGES USING DATA FROM LAND-USE CHANGE AND AGRONOMIC EXPERIMENTS

Modeling Soil Organic Carbon Changes in Conservation Reserve Program Land

In this section, we describe simulation results of changes in soil organic carbon (SOC) documented after six years of converting agricultural land into permanent cover under the Conservation Reserve Program (CRP) at two sites in Texas, two in Kansas, and one in Nebraska (Gebhart et al., 1994). Under the CRP, approximately 17 million ha of erodible land were retired from agricultural production through the establishment of perennial grass cover. This type of land use conversions has been documented to lead to a recovery of the SOM previously lost during cultivation as a result of mineralization and erosion processes (Dormaar and Smoliak, 1985; Post and Kwon, 2000).

At each of the five locations mentioned above, Gebhart et al. (1994) identified fields under crop production, native pasture, and CRP. Salient site characteristics are presented in Table 1. Soil samples to a depth of 3 m were taken from each field at each location in 1992, six years after the land use conversion from cropland to CRP. Sampling increments varied with depth and ranged from 5 cm in the top 0.2 m to 50 cm at depths greater than 1 m. Extra soil cores were taken to calculate soil bulk densities (Mg m^{-3}). These measurements were subsequently used to convert C concentration (g kg^{-1}) into C mass density units (kg ha^{-1}). At each location, differences in SOC determined between native and cultivated sites were ascribed to losses due to cultivation. Concurrently, differences in SOC calculated between cultivated and CRP fields were attributed to SOM recovery due to the establishment of perennial vegetation. Gebhart et al. (1994) reported SOC losses due to cultivation of up to 61% in the top 5 cm. These losses declined to around 15% at depths between 1 and 1.5 m. Only six years after establishment of a perennial cover, the soils at the five sites had recovered on average about 21% of the SOC lost during the period of cropland use. Recovery of SOC reached 34% in the top 5 cm but declined with depth.

Table 1. Changes in SOC observed and simulated in the top 30 cm at five Great Plains sites six years after converting from cropland to perennial grass cover.

State	Site	Soil	Precipitation	Cropping system during cultivation[†]	Net Primary Productivity under CRP in 1992
			----mm----		--kg ha^{-1}--
Nebraska	Valentine	Typic Ustipsamment	480	Corn-sorghum-alfalfa	1100 – 1300
Kansas	Colby	Aridic Haplustoll	500	Wheat-fallow	2000 – 2200
Kansas	Atwood	Aridic Haplustoll	500	Wheat-fallow	2000 – 2200
Texas	Big Spring	Aridic Paleustalf	430	Cotton	800 – 1100
Texas	Seminole	Aridic Paleustalf	430	Cotton	800 – 1100

[†] Plant species names: Corn (*Zea mays* L.), sorghum (*Sorghum bicolor* [L.] Moench.), alfalfa (*Medicago sativa* L.), wheat (*Triticum aestivum* L.), and cotton (*Gossypium hirsutum* L.).

Based on the descriptions given by Gebhart et al. (1994), input soil data files were prepared to simulate with EPIC the impact of land use conversions on SOC content. Simulated and observed SOC stored in the top 30 cm depth of CRP land at five sites, together with the simulated and observed rates of SOC change, are presented in Table 2. The initial SOC content in the top 30 cm ranged from 3408 to 29482 kg ha^{-1}. All land under CRP gained SOC. The observed annual rates of SOC gain ranged from 101 to 2086 kg ha^{-1} y^{-1}. The corresponding rates simulated by EPIC agreed reasonably well with the observed values except for the highest rate documented at Colby, Kansas where a gain of only 733 kg ha^{-1} y^{-1} was achieved. The C sequestration recorded at Colby is unusually high but corresponds well with the level of net primary productivity (NPP) recorded at the site during 1992. In fact, if we were to rank the sites by NPP level in descending order we would find a good match with the ranking of SOC rates. This ranking agreement would also extend to that established for the simulated SOC values.

Table 2. Changes in soil organic carbon (SOC) observed and simulated in the top 30 cm at five Great Plains sites after six years of converting from cropland to perennial grass cover.

State	Site	Initial SOC	Final SOC: Simulated	Final SOC: Observed	Rate of SOC change: Simulated	Rate of SOC change: Observed
			---------kg ha^{-1}---------		--------kg ha^{-1} y^{-1}--------	
Nebraska	Valentine	16834	19282	19800	408	494
Kansas	Colby	29482	33881	42000	733	2086
Kansas	Atwood	27653	31152	32300	583	775
Texas	Big Spring	3408	5451	4500	341	182
Texas	Seminole	3794	6136	4400	390	101

The subroutines introduced in EPIC allow for the quantitative description of C and N transformations in up 14 soil layers of varying depths. The three plots in Fig. 3 present observed and simulated SOC content in reference to the baseline or initial SOC at three of the five CRP sites. In the graphs, the complex pattern of SOC content with depth is given not only by the inherent variability of SOC concentration with depth but also by the changes in soil bulk density and the varying sampling depths. The largest changes in simulated and observed SOC occurred in the upper zone of the soil profiles except at Big Springs, Kansas, where the observed SOC values under CRP at depth were lower than those used as baseline. The simulated SOC values at the same depths revealed a slight increase instead. Understanding SOC changes with depth is deemed of utmost importance for a complete description of the C balance. The application of these fundamental equations to entire soil profiles should yield insight as the fate of C added to soil (e.g., leaching of dissolved organic C). It is anticipated that future versions of EPIC will couple O_2 demand to CO_2 evolution and flux.

Modeling SOC Changes in a Wheat-Fallow System at the Breton Plots, Alberta, Canada

In this section, we use selected results of the long-term Breton Plots (Izaurralde et al., 2001) to test the ability of EPIC to account for SOC changes occurring during 60 years under various crop rotations and fertility treatments. The dominant soil at the Breton Plots is a Typic Cryoboralf developed on glacial till parent material under boreal forest vegetation. There are two crop rotations (two- and five-year cycles) established in factorial combination with nine soil fertility treatments. Here we only describe and discuss results of the two-year rotation (spring wheat [*Triticum aestivum* L.] / fallow) under three fertility treatments. The three fertility treatments considered are a) control, b) commercial fertilizers with N, P, K, and S, and c) cattle manure. Detailed information on rates of fertilizer and manure application is in Izaurralde et al. (2001). A special characteristic of this experiment is that from its inception, all grain, straw (cut by binder), and forage cuts are removed from the plots at harvest.

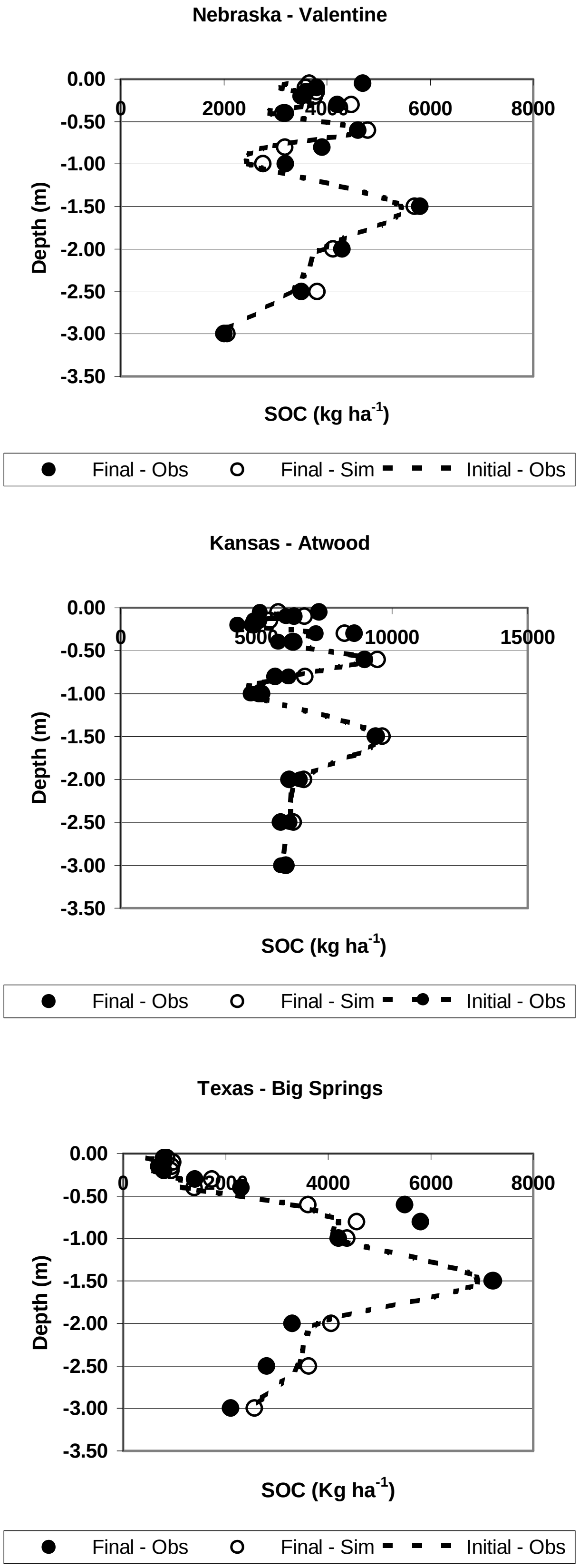

Fig. 3. Simulated and observed SOC with depth at three sites converted to CRP.

Quantitative soil and climate descriptions were used to set up EPIC input files for the simulation runs. Management information (dates of seeding and harvesting, fertilization, etc.) was obtained from a digital database (Izaurralde et al., 1996). The wheat-fallow simulations were conducted for two periods: 1938–1972 and 1972–1998. This was necessary because of a lack of daily weather data for the first simulation period and significant changes in management after 1972. The simulations for the period 1938–1972 used the weather generator. On average, this period had a maximum temperature of 8.2°C while the minimum temperature was -4.1°C. The site averaged about 564 mm of annual precipitation. For the 1972—1998 period, we set up the model to read weather from daily records. On average, the simulation period had a maximum temperature of 9.0°C and a minimum temperature of -3.3°C. The annual precipitation was 586 mm. The daily simulations during the second period accounted for a warming of 0.8°C and a 4% increase in precipitation over the first period. As well, the simulations included the dynamic modeling of atmospheric CO_2 concentrations starting with 295 ppm in 1938 and ending with 365 ppm in 1998.

For the period 1938–1972, the three fertility treatments were: control, fertilizer (N at 11 kg ha^{-1} and P at 8 kg ha^{-1} during the crop year), and manure (N at 305 kg ha^{-1} [12.7 tons, dry] during the crop year). For the period 1972–1998, the three fertilizer treatments were: control, fertilizer (N at 90 kg ha^{-1} and P at 11 kg ha^{-1} during the crop year), and manure (N at 90 kg ha^{-1} during the crop year). Initial SOC concentration in the top 15 cm was 12.9 g kg^{-1}. In 1938, the Passive Humus fraction was initialized at 0.75 while the Biomass fraction was set at 0.02. In 1972, the fractions of the Passive and Biomass compartment were initialized according to how they had ended during the first simulation period. The Passive Humus fraction for the control treatment was 0.88, for the fertilizer treatment was 0.87, and for the manure treatment it was 0.61. The corresponding values for the initialization of the Biomass fraction were 0.001, 0.01, and 0.04.

Realistic modeling of crop yields is required for a correct quantification of C and N additions to soil and their subsequent transformations. In general, wheat yields simulated under the three fertility regimes compared reasonably well with those observed under the same conditions during the two study periods spanning 60 years (Table 3).

Table 3. Simulated and observed yields of wheat grown in a wheat – fallow rotation during two periods spanning 60 years at Breton, Canada.

Fertility treatment		1938-1972	1972-1998
		----------------Mg ha^{-1}----------------	
Control			
	Simulated	1.0	0.0
	Observed	1.0	0.9†
Fertilizer			
	Simulated	1.2	2.0
	Observed	1.5	2.0
Manure			
	Simulated	2.6	2.3
	Observed	1.9	2.3

† Average yield during last three years: 0.2 Mg ha^{-1}.

On average, almost exact matches between simulated and observed yields were obtained in the control treatment during the first simulation period and in the fertilizer and manure treatments during the second. However, a significant departure between simulated and observed yields is noted for the control treatment during the second period. As mentioned before, this “mining” treatment required that the Passive Humus fraction be initialized with a high value of 0.88 at the initiation of the second simulation period. This means that 88% of the total SOC was assigned to the Passive Humus, a compartment with a very long turnover time, which is unable to render significant amounts of available nutrients required for adequate levels of plant growth. The observed yield values, however, reveal that the soil was still able to sustain crops, albeit at a low productivity. As indicated in the footnote of Table 3, however, wheat productivity in the control treatment has been extremely low during the last three years of the study.

Compared to the observed SOC concentration of 12.9 g kg^{-1}, the treatments introduced and maintained for 60 years at the Breton Plots induced significant changes in the final SOC concentrations measured in 1998, which ranged from 8.5 (-34.1%) to 15.3 (10.1%) g kg^{-1} (Table 4).

Table 4. Simulated and observed Soil Organic Carbon in the top 15-cm soil layer during 60 years of a wheat / fallow rotation at Breton, Canada.

Fertility treatment		1938-1972	1972-1998
		----------------g kg^{-1}----------------	
Observed SOC in 1938		12.9	
Control			
	Simulated	10.7	9.5
	Observed	11.3	8.5
Fertilizer			
	Simulated	10.9	10.9
	Observed	13.0	10.2
Manure			
	Simulated	17.4	15.4
	Observed	13.9	15.3

The simulated values mimicked reasonably well the SOC trends observed under the various treatments. The differences between simulated and observed SOC in Table 4 arise from the differences in crop productivity—and consequently C productivity and additions—noted in Table 3. The SOC increase simulated during the first period in the manure treatment and its subsequent decrease during the second, reflect documented changes in C and N inputs (Izaurralde et al., 2001). Although the direction of simulated SOC changes does not match exactly with the observed trends, it demonstrates the sensitivity of the model to one of the major drivers in SOM dynamics, i.e., C inputs.

SUMMARY AND FUTURE WORK

We have described and tested C and N algorithms introduced into EPIC with the objective of converting a well tested and used agro ecosystem model into a comprehensive simulation tool to evaluate impacts of climate, soil, and management on carbon sequestration and environmental quality. The two simulation studies presented and discussed suggest good model performance under a wide range of environmental and management conditions. Notably, the EPIC model now has the basic algorithms to describe gaseous C flows through the soil-plant-atmosphere continuum as well as the lateral transport of C in organic materials and the vertical movement of dissolved organic C below the root zone. The U.S. Department of Agriculture—Natural Resources Conservation Service Headquarters has requested and obtained a version of the EPIC model with the new SOM algorithms for their use in national evaluation of agricultural practices and carbon sequestration. Further tests and model improvements will be conducted using results from long-term experiments from North America, South America, and Europe. Some of these tests will include the evaluation of SOC dynamics as affected by cropping practice, tillage and erosion.

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