Oper Res Int J
DOI 10.1007/s12351-009-0059-1

ORIGINAL PAPER

Modeling organic carbon and carbon-mediated soil processes in DSSAT v4.5

Cheryl H. Porter · J. W. Jones · S. Adiku ·
A. J. Gijsman · O. Gargiulo · J. B. Naab

Received: 27 January 2009 / Revised: 18 June 2009 / Accepted: 23 June 2009

Abstract Cropping systems models have evolved over the last four decades in response to the demand for modeling to address more complex questions, including issues on sustainable production, climate change, and environmental impacts. Early models, which were used primarily for yield gap analysis, have increased in complexity to include not only nutrient and water deficiencies, but also pest and disease damage and processes affecting soil nutrient dynamics. This is the case in the Cropping System Model (CSM) within Decision Support System for Agrotechnology Transfer (DSSAT). This package was developed from various models of individual crops beginning about 25 years ago into one that now has over 25 crops integrated into one program that share many components in a modular format. This modular structure was intended to facilitate incorporation of new components to address those more complex issues. A recent example of this continuing progression is that the CENTURY soil organic matter model was adapted for the DSSAT-CSM modular format in order to better model the dynamics of soil organic nutrient processes. This capability is particularly important to enable CSM to be used for predicting yields in low input cropping systems where soils tend to be deficient in organic matter and nutrients. Organic matter processes are also critical when analyzing the dynamics of cropping systems over long periods of time such as for climate change scenarios. The addition of this more detailed organic matter module

---

C. H. Porter (✉) · J. W. Jones · A. J. Gijsman · O. Gargiulo
Department of Agricultural and Biological Engineering,
University of Florida, 103 Frazier Rogers Hall, PO Box 110570,
Gainesville, FL 32611-0570, USA
e-mail: cporter@ufl.edu

S. Adiku
Agricultural Systems Research Unit, USDA, Ft. Collins, CO, USA

J. B. Naab
Savannah Agricultural Research Institute, Wa, Ghana

provided opportunities to also improve existing components of the model, including energy balance at the soil–plant–atmosphere interface and surface water runoff computations. Conversely, the more detailed organic matter module required additional inputs from existing model components, which were not previously used. Thus, addition of this one new model capability both required and allowed further modifications throughout CSM in order to improve model predictions. This paper provides a brief overview of the DSSAT-CSM model architecture and the DSSAT-CENTURY module and details the changes made to accommodate and take advantage of the more complex soil organic matter modeling capability.

Keywords Crop model · DSSAT · Simulation · Soil · Organic matter

1 Introduction

Cropping systems are highly complex due to the many biological, chemical, and physical processes that affect the productivity of a crop in response to its environment and management. One can generally consider a cropping system to be composed of a crop and the soil on which it is grown, but the environment (physical, chemical, and biological) as well as management actions are also integral determinants of a cropping system's performance. Because of these inherent complexities and a lack of knowledge about how many of these factors interact to affect crop production, researchers only recently started modeling these systems during the last 40 years. These models, such as DSSAT[1] (Tsuji et al. 1994; Jones et al. 2003; Hoogenboom et al. 2004, 2009), APSIM (McCown et al. 1996; Keating et al. 2003), and STICS (Brisson et al. 2003) are usually able to approximate crop and soil dynamics for a rather narrow range of factors that influence soil and crop growth processes under limited conditions.

Rapid progress in this field began once C. T. de Wit and his crop ecology team (De Wit et al. 1974, 1978; Van Ittersum et al. 2003; Bouman et al. 1996) proposed an approach for developing models of cropping systems at different levels of production. In the first level, potential production, the crop is considered to have adequate supplies of water and nutrients, to be well managed, to be free of any biological, chemical, or physical stresses that would reduce growth, and to be affected only by temperature, light, atmospheric carbon dioxide concentration, the plant's genetic characteristics, and plant geometry. Models at this level provided researchers with a very useful tool to estimate potential production of a crop for any given site for comparison with actual production, thereby quantifying the yield gap. A second level added resource limitations, typically one at a time, such as water and/or nitrogen. Models at this level, for example, allowed for the study of rainfall limitations, irrigation management, nutrient management, and soil physical properties on growth and yield. The third general modeling level facilitates the incorporation of pests and diseases as well as other types of stressors that damage

---

[1] DSSAT ©1983–2009 International Consortium for Agricultural Systems Applications.

tissue and reduce productivity under actual production conditions (Boote et al. 1983).

By following this logic, it is easy to see how these characterizations led to progress, but it also suggests how complex models become as one incorporates more factors important under many real production situations. One can also see the need for development of modular models such that new components can be incorporated as knowledge is gained and as production situations become more complex (Jones et al. 2001, 2003; Keating et al. 2003). The DSSAT cropping system model is one widely used model that has a modular structure (Porter et al. 2000; Jones et al. 2003). This modular structure was developed to facilitate model maintenance and to include additional components to simulate cropping systems over a wide range of soils, climates, and management conditions, including those in developing as well as developed countries. It was also developed to allow users to study changes in soil dynamics and production of crops grown in rotations over years in response to management and climate conditions.

The goal of this paper is to describe how one important new component was developed and integrated into the DSSAT cropping system model and how the complexities of this integration demonstrate practical limits to rapid progress toward more comprehensive models; particularly, models that accurately represent all factors in poorly managed and degraded soils in harsh climates. In particular, we focus on development of a key component in low input cropping systems, the soil organic matter (Lal 2007) and by extension, the organic matter-mediated soil processes. Soil organic matter (SOM) is a repository of plant nutrients which are released via microbial decomposition. In addition, soil organic matter is the major source of soil carbon, which is involved in many physical and chemical processes in the soil. Even though some carbon is lost during the decomposition of organic matter, management practices that enhance the soil organic matter could help minimize the rising atmospheric carbon load. It is noteworthy that even under high input management systems where large amounts of soluble nutrients are supplied, hence minimizing the role of organic matter in supplying nutrients, the role of organic matter in enhancing soil productivity via the modification of soil process (e.g., structural stability, porosity enhancement, increased soil water availability, among others) cannot be overlooked.

Many models of SOM have been developed and used for various purposes (McGill 1996). CENTURY (Parton et al. 1988) and RothC (Jenkinson and Rayner 1977) are two widely used SOM models. These models represent extremes in a range of complexity and accessibility (FAO 2004) and have been historically evaluated over a range of environments. In a model comparison exercise, Smith et al. (1997) compared nine SOM models and found similar performance across models. CENTURY has been adapted for use in the DSSAT cropping system model (CSM) (Gijsman et al. 2002). The Gijsman et al. version of CENTURY was subsequently integrated into the modular structure of DSSAT (Jones et al. 2003), but it did not include the interactions of soil organic matter with other important components in CSM. The importance of incorporating these interactions is highlighted in Fig. 1, which also shows the primary and secondary modules in CSM. The soil organic matter modules in CSM, shown in the figure, are affected by

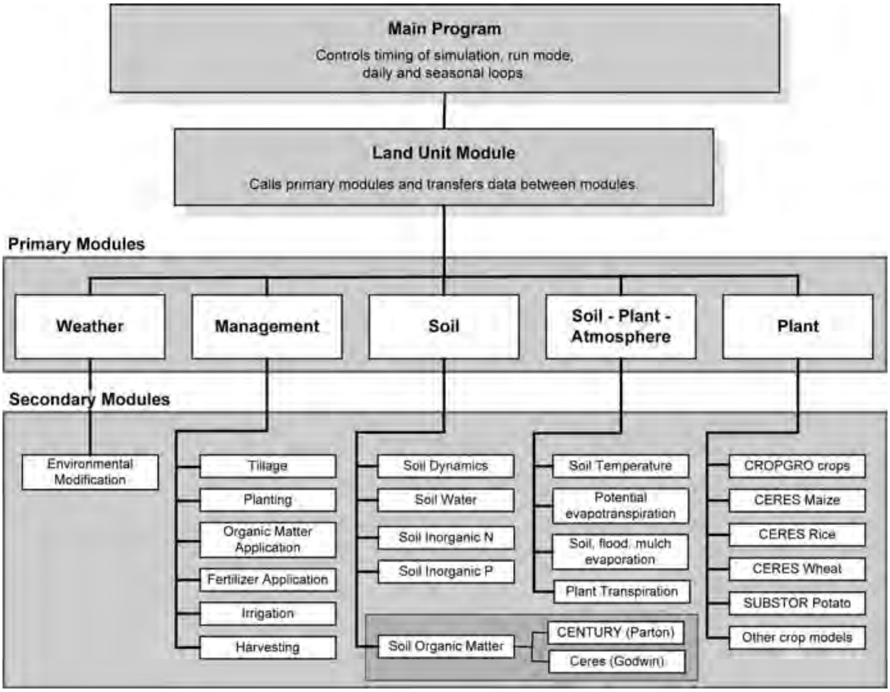

Fig. 1 Primary components of DSSAT-CSM (based on Jones et al. 2003). Two soil organic matter modules are currently provided under the Soil primary module: the CENTURY and CERES-based models

or in turn affect the dynamics of all other modules. This integration requires the establishment of the relevant quantitative relations for these interactions and subsequently of including these relationships into crop models. In this paper, we present the concepts for modeling the SOM and SOM-mediated soil processes in the DSSAT-CSM.

The primary objective of this paper is to describe how the addition of the CENTURY model to the DSSAT-CSM presented additional complexities throughout the model as well as provided opportunities to improve prediction capabilities in modules other than DSSAT-CENTURY. A secondary objective is to demonstrate the sensitivity of the model to various soil organic carbon-related factors or inputs.

2 Model description

2.1 Overview of DSSAT-CSM

The DSSAT-CSM simulates growth, development and yield of a crop growing on a uniform area of land under specified management. The dynamics of soil water, carbon, nitrogen and phosphorus that take place in the cropping system over time are also simulated. The model is structured using the modular approach described by Jones et al. (2001) and Porter et al. (2000) and consists of a main driver program, a land unit module, and primary modules for weather, management, soil, plant, and soil–plant–atmosphere interface components (Fig. 1). Collectively, these components describe the time changes in the soil and plants that occur on a single land unit in response to weather and management on a daily basis.

The modular structure of the model allows for multiple components with the same function (i.e., components which provide the same output with different computation algorithms) to be linked, providing flexibility to users and model developers and allowing evaluation and comparison of different model formulations. An interface explicitly defines the required data transfer to and from each module. CSM contains two options for modeling soil organic matter accumulation and decomposition: the DSSAT-CENTURY model (Gijsman et al. 2002; Parton et al. 1992) and the CERES-based soil organic matter model (Godwin et al. 1998). However, discussions in this document focus on the DSSAT-CENTURY option. Both modules transfer data using the same data interface and thus it is possible to replace either module with yet a third soil organic matter module, with little modification of source code, provided that the module interface is maintained.

The DSSAT-CSM is a product of many scientists and engineers working in a coordinated way, but independently in various parts of the world. The modular structure of CSM is critical to the evolution of the model and allows this “quasi open source” development method to continue effectively. The adaptation of a new module, DSSAT-CENTURY for example, can allow new modeling capabilities to be added to existing modules, each of which may be maintained by a different person or group. Conversely, it may require existing modules to provide data that previously were not required by any other module. Although computation of the various SOM constituents and processes are isolated within the SOM modules, the dynamics of the organic C impact or are impacted by every other module in CSM. Table 1 presents the components and processes, as modeled by the DSSAT-CSM, which either (1) affect the accumulation or decomposition of organic matter; or (2) are affected by soil or surface organic matter dynamics. Also listed in Table 1 are the primary modules in which each component or process is computed and the associated model changes for implementation of that component or process. Descriptions of processes in this document are organized by these two broad categories.

The DSSAT-CENTURY model was included in the DSSAT v4.0 release in 2004 (Hoogenboom et al. 2004). Substantial modifications were made to the model at that time to accommodate the daily time step of CSM (compared to the monthly time step in the original CENTURY model) and to conform to the modular format of CSM. These changes are covered in more detail in the publications by Gijsman et al. (2002) and Jones et al. (2003).

Once the CENTURY model was fully integrated into the DSSAT-CSM, the ability to use outputs from the more detailed organic matter model became possible. Use of the DSSAT-CENTURY model also revealed deficiencies, such as the inflexibilities in initializing the various pools of organic matter. Modifications to the DSSAT-CENTURY model since the original release with DSSAT v4.0 include the addition of organic phosphorus modeling, improved initialization routines to

Table 1 DSSAT-CSM components used to model soil organic matter

Component or process	Primary Modules	How organic matter is affected	Model changes implemented
Components or processes which affect quantities of organic matter			
Tillage	Management	Redistribution and mixing of organic matter and other soil constituents; increases decomposition rate	Calls to mixing routine added to CENTURY module
Organic matter application	Management	Addition of organic matter to soil and surface	Additional residue properties, such as lignin content, water holding capacity, and light extinction coefficient were required
Soil moisture	Soil	Affects decomposition rate	None
Inorganic N or P	Soil	Can limit decomposition rate in nutrient-poor systems	None
Soil temperature	Soil–Plant–Atmosphere	Affects decomposition rate	None
Senescence of plant tissue and harvest residues	Plant	Addition of organic matter to soil and surface	Plant growth routines modified to track senesced tissue and harvest residue, including N, P and lignin concentrations. Additional input data were required for some crop models
Component or process	**Module**	**How soil component or process is affected**	**Changes required**
Components or processes affected by surface or soil organic matter			
Soil properties	Soil	Soil organic matter can change bulk density and water holding capacity of soils	Soil properties modification added to Soil dynamics module
Surface water runoff	Soil	Mulch layer increases surface storage capacity and roughness thereby decreasing runoff	New mulch water balance routine added. Changes to surface runoff routine
Inorganic N or P	Soil	Decomposition of organic matter can immobilize or mineralize N and P	None
Soil evaporation	Soil–Plant–Atmosphere	Affects surface albedo and therefore potential soil evaporation. Shading and preferential evaporation decrease evaporation from soil	Modification to soil evaporation routine

allow flexibility in user input, improved functions for the response of organic matter decomposition to soil water and temperature, and mixing of organic matter constituents with a tillage event. All of these improvements, except organic phosphorus modeling, are discussed in more detail in the following sections.

2.2 Overview of organic C modeling in DSSAT-CENTURY

A schematic diagram of the components modeled in DSSAT-CENTURY is presented in Fig. 2. The module maintains three soil organic matter (SOM) pools and two pools of fresh organic matter (FOM or litter) both in and on top of the soil:

- SOM1—microbial or active material,
- SOM2—recalcitrant material (e.g., derived from lignin, cell walls), decomposed SOM1 and stabilized microbial material (e.g., microbes that are physically protected by the soil structure), and
- SOM3—the largely inert material and stabilized microbial material.
- Metabolic litter—easily decomposable fresh residue (e.g., proteins, sugars),
- Structural litter—recalcitrant fresh residue (e.g., lignin, cell walls).

Decomposition occurs on the order of days for SOM1 and the two litter components; years for SOM2; and hundreds of years for SOM3. Organic nitrogen and phosphorus contents are maintained in each organic matter pool for each surface and soil layer.

Accurate initialization of the various organic matter pools is critical in adequately modeling the dynamics between organic and inorganic components and the soil fertility of a cropping system. In many cases it is difficult to obtain data to precisely determine initial conditions for a site. As the DSSAT-CENTURY model was applied in low-input cropping systems, many with nutrient deficient soils, it became

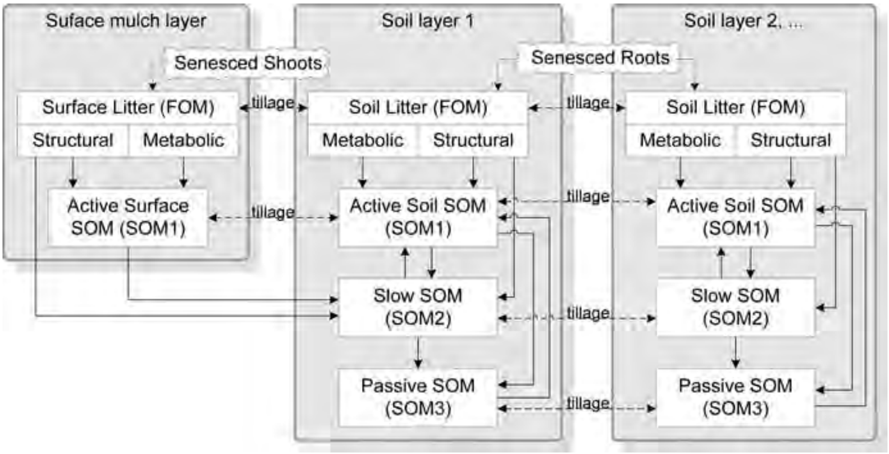

Fig. 2 The carbon pool and flow structure of the DSSAT-CENTURY organic matter module. Units are kg ha^{-1} for mass pools and kg ha^{-1} day^{-1} mass flows. Based on the work of Gijsman et al. (2002) and Parton et al. (1992)

apparent that the initialization methods of the original CENTURY model, which was developed with data from temperate regions, were not applicable for all cropping systems. The DSSAT-CENTURY model was modified to allow more flexibility with user-supplied data. Initialization of organic matter components is now determined by the type and quality of input data that the user provides. Proportions of the various pools of soil organic matter can be more precisely specified, if measured data are available.

2.2.1 Total organic carbon

Total organic carbon, represented as a percent on a mass basis (g[C]/100 g[soil]) is specified for each soil layer in the soil profile data file. These initial values represent background soil organic matter specific to each layer for the specified soil type. Alternatively, field measurements of total organic carbon should be provided by the user. These values, if provided for a specific experiment or field situation, override the more generic values in the soil profile data.

2.2.2 Fresh organic matter

FOM from a previous crop can be specified by the user. Both surface and soil residues are listed by dry weight of root, nodule and surface residue, all in kg ha^{-1}. An external DSSAT data file provides additional information on lignin, nitrogen and phosphorus contents for various crop types and for surface and sub-surface crop residues. The lignin content is used to partition the crop residues into structural and metabolic components, which decompose at different rates.

2.2.3 Soil organic matter pools

The total soil organic matter is divided into the two FOM pools and the three SOM pools. The fertility of some soils can be very sensitive to the initial fractions assigned to these pools. Quickly decomposing organic matter can provide large amounts of inorganic nutrients to a crop in a single year, whereas more slowly decomposing organic matter may provide very little.

The total organic matter in the soil, but not on the soil surface, is assumed to be composed of FOM (i.e., litter incorporated from a previous crop) and humic organic matter or SOM. The assumption that FOM is included in the total measured carbon is based on studies in West Africa (Bado et al. 2004; Bostick et al. 2006) where the measurements of organic C over time revealed high decomposition rates consistent with a high proportion of fresh organic matter in the decomposing soil organic matter. Thus, to initialize the total SOM carbon, the FOM carbon in the soil is subtracted from the total measured organic carbon. The remaining amount is then proportioned among the three SOM pools. The DSSAT-CENTURY model estimates the fraction of stable organic carbon (SOM3 fraction) in the soil by one of three methods described below. The method used by the model is dependent on input data provided by the model user. Once stable C (SOM3) has been estimated, the fractions of SOM1 and SOM2 are assumed to be 5% and 95% of the remaining amount, respectively.

1. *Direct input of Stable Organic C.* When the amounts of stable and total organic C in each soil layer have been measured, these data can be input as experimental data. This method provides the most reliable simulations and allows flexibility in directly controlling the fractions of organic matter pools. However, stable organic C is very difficult to directly measure, and most users are not expected to have this measurement.
2. *Field history and duration.* Estimates can be made of initial soil organic matter fractions using results which were obtained by running a series of long-term simulations of CSM with different management practices, soil types and initial conditions. The results of these simulations were tabulated in an external DSSAT file. The model indexes these values of stable carbon fraction using two input parameters: a field history code, representing a management scenario, and the duration in years that the management scenario had been in effect prior to the start of simulation. Each field history code represents a combination of the level of management (irrigation, fertilizer, residue left in field) as well as the condition of the soil at the beginning of this management regime (grasslands, cultivated, degraded). Each field history code provides a stable organic C (SOM3) amount, expressed as a fraction of total soil organic C, for two soil depths (0–20 and 20–40 cm), 12 soil textures, and six management durations (0, 5, 10, 20, 60 and 100 years).
3. *Regression equation.* A dataset of soil carbon and texture collected in over 300 fields in Northern and Southern Ghana by J. Koo, J. B. Naab, S. Adiku, and P. S. C. Traore (see Koo 2007, Chap. 2) was used to estimate stable soil carbon. When total soil organic carbon was plotted against silt plus clay content, there was a range of observed values for any particular soil texture. The lowest soil carbon observed for any given value of silt plus clay content was assumed to be an estimate of the stable soil organic carbon (John Duxbury, personal communication). A regression equation was fit to these lowest carbon values as shown in Eq. 1, below. This equation is used in the model to estimate the stable carbon pool (g[C]/100 g[soil]).

$$\text{StableC} = 0.015 \cdot (\text{Clay} + \text{Silt}) + 0.069 \tag{1}$$

where StableC is the stable organic C (SOM3), Clay is the soil clay content, and Silt is the soil silt content, all in units of mass percent or g[soil component]/100 g[soil]. This equation is similar to the one reported by Duxbury (2006) for soils used in rice cropping systems in South Asia; ($\text{stableC} = 0.0185 \cdot (\text{Clay} + \text{Silt}) + 0.0064$). Equation 1 was found to be generally valid for data published for coarse-textured soils in Poland and Germany (Kiem 2002), China (Zhao et al. 2006), South Africa (Lobe et al. 2001), India (Battacharyya et al. 2007) and Brazil (Zinn et al. 2007).

Thus, if no direct measurements or field history data are available, Eq. 1 is applied. It should be noted however, that these values represent the physically protected soil carbon and may underestimate stable soil carbon for some clay soil types which also contain significant portions of biochemically protected soil carbon.

2.3 Accumulation, decomposition and redistribution of organic matter

Quantities of organic matter in each pool are updated daily in CSM based on the rates of additions of organic matter, transformations among the pools due to decomposition, and losses of organic matter from the system. Each of these processes contributing to mass flows is discussed below.

2.3.1 Additions of organic matter

Organic matter applications are specified as model inputs, including residue application date, type, amount, concentrations of N and P, incorporation percentage, incorporation depth, and application method. An external file is available to provide residue properties that may be missing from input data, but are needed by the model. The CSM management module controls the dates, types and amounts of organic matter applications, but the CENTURY module maintains the surface and soil state variables for the various dry matter quantities and carbon pools.

Quantities of senesced plant matter are added to surface and soil FOM. Each crop growth module determines the rates of senescence of tissue and the N, P and lignin concentrations in that tissue and sends this information to the CENTURY soil organic matter module. The components of senesced plant matter are added to the metabolic and structural litter pools for the surface and soil layers on a daily basis.

For simulating crop rotations over multiple seasons, the residue left in the field after a harvest is added to soil and surface FOM pools. Dry weight, N, P and lignin concentrations for each plant component are added to either surface or soil layers.

It was necessary to modify the crop growth modules in CSM to provide the additional quantities of organic matter from senesced tissue and harvest residues and their chemical composition. Some plant composition characteristics were established in an external look-up file to allow flexibility. A generic harvest module was developed to process the plant organic matter data to minimize code redundancy and to facilitate the addition of new crop modules in the future.

2.3.2 Decomposition of organic matter

Decomposition of organic matter is computed on a daily basis in the DSSAT-CENTURY module. This decomposition shifts the amounts of organic matter from more active forms (FOM and SOM1) to more stable forms (SOM2 and SOM3). Figure 3 presents a simplified schematic of the flow of matter between pools in the decomposition process.

Decomposition rates for each of the organic matter pools are functions of first order rate constants modified by temperature, moisture, cultivation, and texture factors (Parton et al. 1994):

$$\frac{\mathrm{dC}}{\mathrm{d}t} = -k_t \cdot \mathrm{C} \tag{2}$$

and

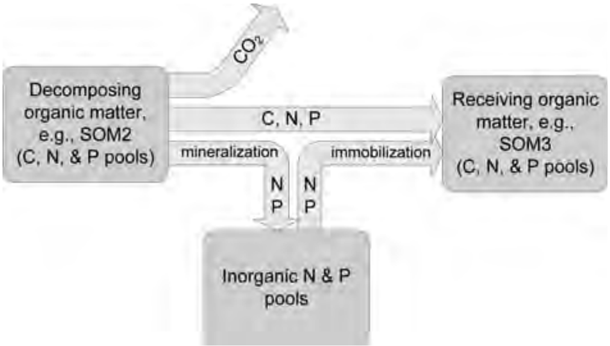

Fig. 3 Example of flows of C, N and P from a decomposing organic matter pool in Fig. 2 to another organic matter pool. N and P can be either immobilized or mineralized in the process. Carbon is lost as CO_2 to the atmosphere

$$k_t = k_0 \cdot \mathrm{TF} \cdot \mathrm{WF} \cdot \mathrm{CF} \cdot \mathrm{TXF} \tag{3}$$

where C is the organic carbon present in decomposing pool (kg ha^{-1}), t is the time step in days, k_0 and k_t are the base and modified rate constants (day^{-1}), TF, WF, CF and TXF are the temperature, water, cultivation and texture factors, respectively.

The carbon released by decomposition is partly mineralized to CO_2 and the remaining C is transferred to one or more other organic matter pools (Figs. 2, 3). Other factors such as SOM quality and soil texture affect the flow of organic matter among decomposing pools. For example, the lignin content of the litter affects the relative amounts of decomposing litter that are added to the microbial (SOM1) and the slow (SOM2) pools. Soil texture, in addition to modifying the rate of SOM1 decomposition, controls the partitioning of C flow between two or more receiving pools. Table 2 presents a summary of the decomposition rates and modifiers associated with the transformations of the various organic matter pools.

The surface mulch layer is maintained separately from the soil layers and contains structural and metabolic litter pools and a microbial pool. As this organic matter layer decomposes, any intermediate and stable organic matter (SOM2 and SOM3) generated is added to the pools in the top soil layer.

2.3.2.1 Temperature factor The temperature factor (TF, Fig. 4) used to modify decomposition rates in the DSSAT-CENTURY model is based on the work presented by Lloyd and Taylor (1994). An empirical equation computes a temperature factor which decreases decomposition rates below 24.6°C and increases decomposition above that temperature.

$$\mathrm{TF} = \mathrm{TF}_{10} \cdot \exp\left[5.51 - \frac{308.56}{T + 46.0}\right] \tag{4}$$

where TF10 is the value of TF at 10°C (=0.32) and T is the daily average soil temperature (°C). A temperature factor is computed for each soil layer each day and applied to increase or decrease decomposition rates for all organic matter

Table 2 Summary of decomposition rate modifiers in DSSAT-CENTURY model

From	To	Base decomposition rate k_0 (day^{-1})	Rate modification factors[a,b,c]	Respiration Losses (fraction)[b,d]
Metabolic litter	SOM1	0.04055 (surface)		0.55
		0.05068 (soil)		
Structural litter	SOM1	0.01068 (surface)		0.45 (surface)
		0.01342 (soil)		0.55 (soil)
	SOM2	0.01068 (surface)		0.3
		0.01342 (soil)		
SOM1	SOM2	0.01644 (surface)	$0.25 + 0.75 \cdot \mathrm{SAND}$	$0.17 + 0.68 \cdot \mathrm{SAND}$
		0.02000 (soil)	SLNF (soil file input)	
	SOM3	0.02000 (soil only)		
SOM2	SOM1	0.000548 (soil only)	SLNF (soil file input)	0.55
	SOM3	0.000548 (soil only)		
SOM3	SOM1	0.000012 (soil only)	SLNF (soil file input)	0.55

In addition to rate modifiers listed, water, temperature and cultivation rate modifiers are also applied to all decomposition rates (Parton et al. 1987; Gijsman et al. 2002)

[a] All decomposition rates are modified by temperature and water factors (TF and WF), which are computed daily. A cultivation factor (CF) of 1.6 accelerates decomposition for a period of 30 days after tillage or incorporation of organic matter into the soil for all pools except metabolic litter, which is unaffected by cultivation

[b] SAND is fraction of sand content by mass (g[sand]/g[soil])

[c] SLNF is an input parameter to account for soil mineralization factors not modeled

[d] Respiration losses represent the fraction of C which is lost to the system as CO_2 during the decomposition process

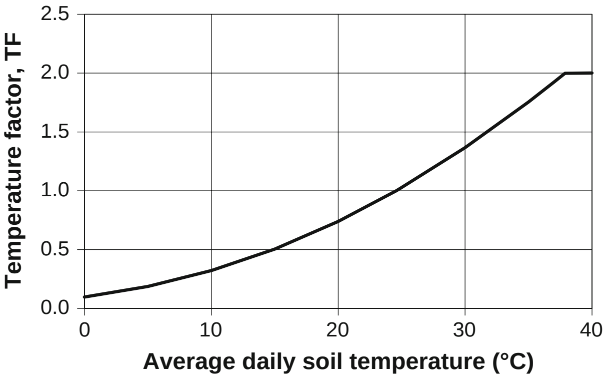

Fig. 4 Temperature factor function adapted from Lloyd and Taylor (1994)

constituents in that layer. Surface organic matter is modified by the factor for the top soil layer. A maximum value of 2.0 is used for this factor.

2.3.2.2 Water factor The DSSAT-CENTURY model decreases decomposition rates for both wet and dry soils. The water factor (WF, Fig. 5) is computed daily as a

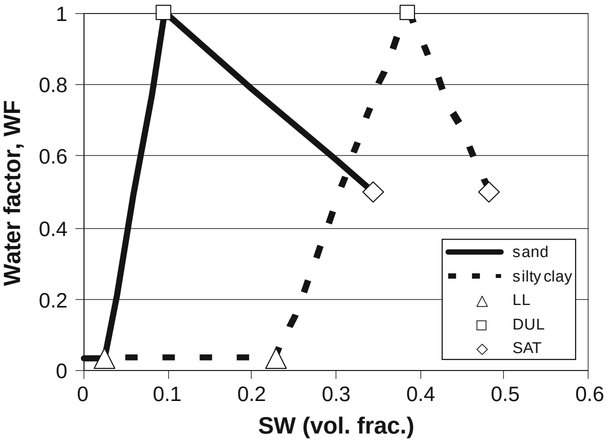

Fig. 5 Water factor function for two soil types. The decrease in decomposition is a function of soil water content relative to LL, DUL and SAT (after Godwin et al. 1998; Adiku et al. 2008)

function of soil water content and the water contents at lower limit, drained upper limit and saturation (all in volumetric fraction) for each soil layer. This function is based on the work of Godwin et al. (1998) and Adiku et al. (2008).

2.3.2.3 Soil texture factors Soil texture directly affects SOM and residue decomposition so that, with increasing clay content, there is: (a) a reduced decomposition rate of soil microbial organic matter (SOM1); (b) a reduced fraction of CO2 lost with decomposition of SOM1; (c) an increased partitioning of the flow out of SOM1 toward stable SOM3 and a reduced flow to intermediate SOM2; (d) an increased partitioning of the flow out of SOM2 toward stable SOM3 and a reduced flow from SOM2 toward active SOM1; and (e) a modified multiplier to accommodate for the effect of soil water conditions on decomposition rates.

2.3.2.4 Cultivation factor A cultivation factor increases the decomposition rate for a period of 30 days after a soil disturbance. This rate is 1.6 for all soil carbon pools except metabolic litter, which is unaffected by cultivation (Parton et al. 1994; Gijsman et al. 2002). For uncultivated soils, the modifier is set to 1.0 so that there is no affect on decomposition rates.

2.3.3 Redistribution of organic matter

Organic matter components can be redistributed from surface to soil or among layers within the soil profile when tillage occurs or when organic matter applications are incorporated into the soil. When incorporation of surface residues is specified by tillage or residue application events, the surface residues are mixed into the top soil layers to the depth and at an incorporation percentage specified in a file that contains characteristics of different tillage operations. If none, or only a partial, residue incorporation is specified, a mulch layer is maintained on the surface.

Tillage events also result in a blending of soil components within the specified tillage depth. The mixing efficiency, or percentage of soil that is mixed, is a user-specified input for each tillage operation. Soil components are mixed at the specified percentage, including soil water, inorganic soil nutrients, soil texture components and all organic matter pools.

2.3.4 Comparison with measured values

As an example of simulated organic matter dynamics, Fig. 6 presents a comparison of simulated and measured organic carbon for a sandy loam soil in Burkina Faso, West Africa (Bado et al. 2004; Bostick et al. 2006). The 11-year experiment was comprised of a rotation of sorghum (*Sorghum bicolor* (L.) Moench) and fallow native grass with no fertilizer or irrigation applications. Prior to the first planting, the field was taken out of bush fallow and contained a relatively high amount of FOM. This initial FOM was estimated in the model by simulating an initial six-year spin-up simulation of brachiaria grass. For the 11-year rotation, sorghum was planted when the rainy season began in June or July of each year and was harvested at maturity in October or November. Native grasses grew sparsely in the field between harvest and the next planting and were modeled as bare fallow during that period. Plots were moldboard plowed before planting, thus incorporating FOM from the surface to the soils annually.

The initial high FOM resulting from the native grasses was tilled into the soil prior to the first planting, resulting in the spike of soil organic matter early in the simulation. This FOM was depleted quickly, but was partially replenished during the annual fallow periods. Active SOM1 follows a similar pattern. SOM2

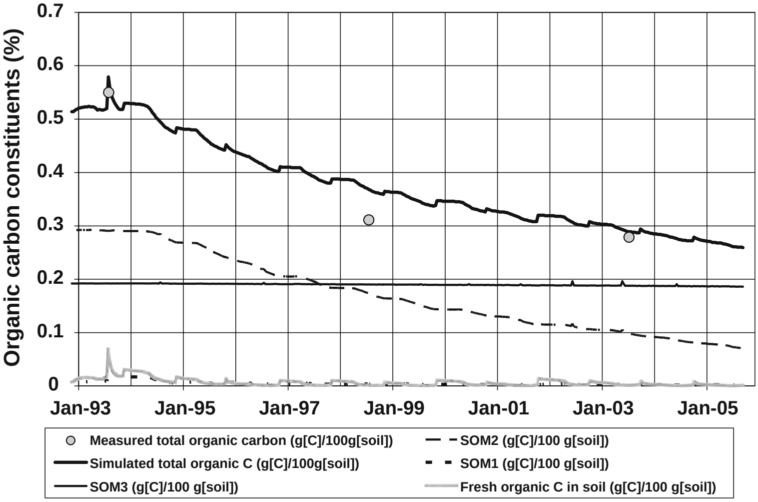

Fig. 6 Simulated and measured organic carbon for a long-term sorghum-fallow rotation on a sandy loam in Burkina Faso (Bado et al. 2004; Bostick et al. 2006), showing the relative rates of decomposition simulated for soil organic matter constituents

decomposed at a relatively fast rate early in the simulation with a declining rate later as SOM2 stores were decreased. SOM3, the stable organic matter pool, remained nearly constant over the simulation. The measured values, also shown in Fig. 6, corresponded well with the simulated total soil organic C values for the 11-year experiment.

2.4 Effects of soil and surface organic matter accumulation

The accumulation of organic matter in the soil and on the surface affects several critical soil properties and processes including bulk density, water and nutrient holding capacities, water infiltration rates, soil crusting, surface water runoff rates and erosion. In addition, decomposition of organic matter can release or immobilize inorganic nutrients thus changing the fertility of the soil. Atmospheric carbon dioxide is released during the decomposition process. Some of these factors are modeled by CSM as described in the following sections.

2.4.1 Release of inorganic N and P to soil

As organic matter decomposes, the associated mineralization processes release N and P to soils. This can be very important in soils that are nutrient deficient and not fertilized. Figure 2 shows a schematic of the C pools modeled by DSSAT-CENTURY and Fig. 3 further highlights the flow of C, N, and P among decomposing pools. The following discussion refers to nitrogen dynamics in the decomposition process, but phosphorus dynamics in the model follow similar logic. Each of the flows of carbon from one pool to another is accompanied by an amount of N that is proportional to the C:N ratio of the decomposing material. If the N content of the decomposing organic matter from the source pool is greater than that required by the recipient pool, then excess inorganic N is released into the surrounding soil by mineralization and becomes available for plant uptake. Conversely, if the N content of the decomposing pool is less than that required by the recipient pool, then additional N needed for adding C to the recipient pool is obtained by immobilizing some inorganic N from the surrounding soil. When decomposition is accompanied by immobilization, N or P deficiency in the soil can limit decomposition rates.

Figure 7 shows an example of the nitrogen dynamics associated with the transformation of organic N to inorganic N through mineralization as simulated by the DSSAT-CENTURY model. This simulation approach uses soils and weather data collected from a long-term fallow experiment at Rothamsted, UK (Jenkinson et al. 1987; Gijsman et al. 2002) conducted on a silty clay loam soil. Organic N in the soil decreased due to decomposition of soil organic matter. The process of mineralization, associated with decomposition, released inorganic N to the soil, thus the slopes of the organic N and mineralized N lines (lines (d) and (b) in Fig. 7) are equal, but opposite in sign. The inorganic N, line (c), was increased by the amount of mineralization except when N was leached from the soil profile by drainage.

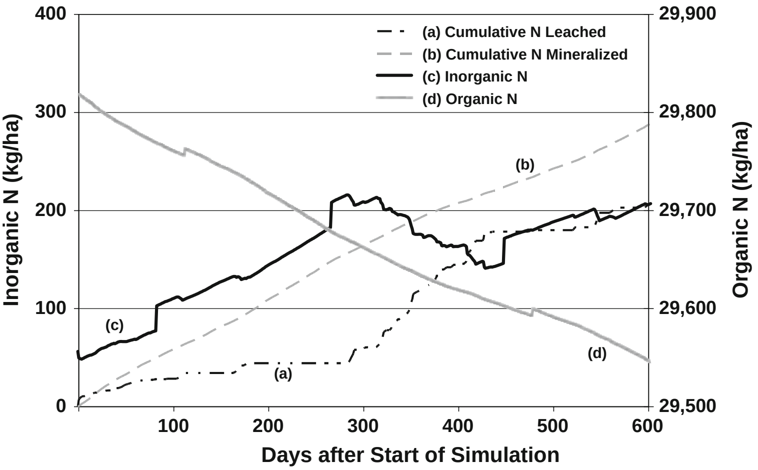

Fig. 7 Effects of SOM decomposition on soil N for a bare fallow soil treatment using soil and weather data from a long-term fallow experiment at Rothamsted, UK (Jenkinson et al. 1987; Gijsman et al. 2002). Organic N decreases as mineralization proceeds. Inorganic N increases due to mineralization and decreases due to leaching

2.4.2 *Effect of organic matter on soil properties*

2.4.2.1 Soil bulk density As organic matter is added to the soil, the bulk density is decreased and the soil layer thickness is increased. As presented by Adams (1973), the bulk density of a soil can be computed as the composite of its mineral and organic matter components:

$$\mathrm{BD} = \frac{100}{\left(\frac{\mathrm{SOM\%}}{\mathrm{BD_{SOM}}}\right) + \left(\frac{100 - \mathrm{SOM\%}}{\mathrm{BD_{mineral}}}\right)} \tag{5}$$

where BD, $\mathrm{BD_{mineral}}$, and $\mathrm{BD_{SOM}}$ are the bulk densities of the soil, mineral and SOM components, respectively, all in g $\mathrm{cm^{-3}}$; and SOM% is the soil organic matter content (mass percentage or g[dry organic matter]/100 g[soil]). While the bulk density of soil organic matter is fairly consistent, the mineral bulk density is not consistent and the value is not usually known. To circumvent this problem, CSM v4.5 uses a method similar to that of the EPIC program (Izaurralde et al. 2006) to estimate mineral bulk density at the initiation of the run based on initial values of soil bulk density and soil organic matter content.

Equation 5 is rearranged to compute mineral bulk density, $\mathrm{BD_{mineral}}$, using the user-supplied initial values of soil bulk density and a $\mathrm{BD_{SOM}}$, of 0.224 g[dry organic matter] $\mathrm{cm^{-3}}$.

$$\mathrm{BD_{mineral}} = \frac{100 - \mathrm{SOM\%_{init}}}{\left(\frac{100}{\mathrm{BD_{init}}}\right) - \left(\frac{\mathrm{SOM\%_{init}}}{\mathrm{BD_{SOM}}}\right)} \tag{6}$$

where $\mathrm{SOM\%_{init}}$ and $\mathrm{BD_{init}}$ are the initial SOM content (g[dry organic matter]/100 g[soil]) and initial bulk density (g $\mathrm{cm^{-3}}$) of the soil. It is assumed that the bulk densities of organic matter and mineral matter remain unchanged throughout the simulation. Then the overall soil BD is updated daily based on Eq. 5, using the static values of $\mathrm{BD_{mineral}}$ and $\mathrm{BD_{SOM}}$ and the current SOM content.

The increase in soil layer thickness due to addition of organic matter is approximated by Eq. 7, which assumes that the increase in layer thickness is proportional to the amount of organic matter added. The authors have verified with a more detailed iterative algorithm that this approximation is correct to within 10^{-4} cm for a wide range of organic matter applications.

$$\theta_{\mathrm{SATm}} = S_m \cdot M_{\mathrm{mulch}} \cdot 10^{-4} \tag{7}$$

In Eq. 7, ΔDlayr is the change to soil layer thickness (cm), ΔSOM is the change to soil organic matter content (kg[dry organic matter] ha^{-1}) and $\mathrm{BD_{SOM}}$ is 0.224 g[dry organic matter] cm^{-3}.

The modifications to BD and soil layer thickness generate base values onto which tillage effects are superimposed. After a tillage event, rainfall kinetic energy settles the soil to the bulk density and layer thicknesses that have been updated based on organic matter content at each time step. Figure 8 depicts the process and flow of data in CSM for modification of soil properties with tillage or addition of organic matter. Figure 9 illustrates these dynamic soil properties with results from simulation of a hypothetical field with sandy loam soils under tilled and untilled conditions. The base value of bulk density was modified due to the addition of large amounts of organic matter for both tilled and untilled conditions. The effects of tillage on bulk density are much greater than the effects of adding large amounts of residue to the field. After a tillage event, the soil settles to the bulk density that was computed using the organic matter, and so the effects of tillage are transient.

2.4.2.2 Soil water holding capacity Addition of organic matter to the soil increases the capacity of the soil to retain moisture. CSM uses relationships developed by Gupta and Larson (1979) to quantify changes to the field capacity or drained upper limit (θ_{DUL}) and the wilting point or lower limit (θ_{LL}) of a soil based on changes to organic matter. These relationships are based on a regression of soil water content and soil composition:

$$\theta = A \cdot \mathrm{Sand} + B \cdot \mathrm{Silt} + C \cdot \mathrm{Clay} + D \cdot \mathrm{SOM\%} + E \cdot \mathrm{BD} \tag{8}$$

where θ represents either θ_{LL} or θ_{DUL}; A, B, C, D and E are regression coefficients specifically applicable to each response variable; and Sand, Silt, Clay and SOM% are the mass percentages of each soil component. The values of the regression coefficients are listed in Table 3. The SOM% term in Eq. 8 includes both SOM and FOM. The total mass of organic matter is computed from mass of C, using conversions 1.9 g[SOM]/g[SOM−C] and 2.5 g[FOM]/g[FOM−C], and then converted to percentage units.

Equation 8 is not used to initialize the water holding capacity of the soil, but rather to update the values of θ_{DUL} and θ_{LL} due to changes in organic matter or bulk density after the simulation is started. It is assumed that the sand, silt, and clay components of the soil column do not change over the course of a simulation, except

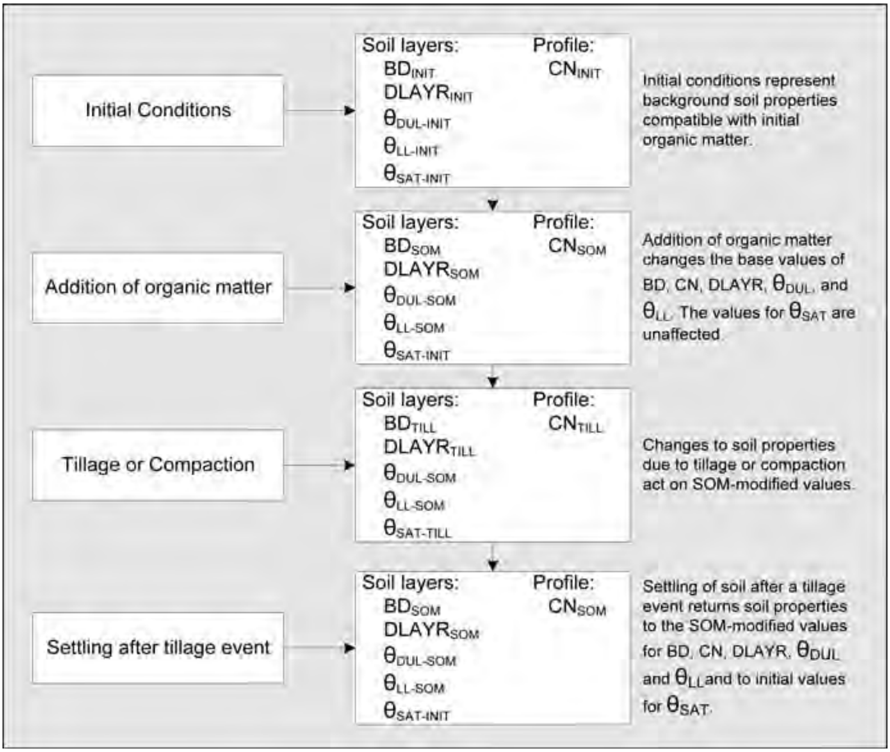

Fig. 8 Modification of soil properties due to changes in soil organic matter and tillage events in DSSAT-CSM

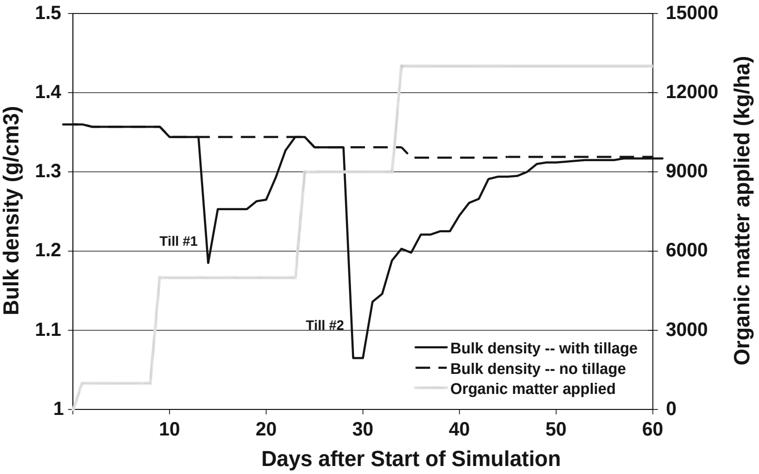

Fig. 9 Simulated changes to soil bulk density for a sandy loam soil due to additions of organic matter to soil for tilled and untilled conditions

Table 3 Regression coefficients relating water holding capacity to soil characteristics

Soil constituent or property → Regression coefficients →	Sand (g/100 g) A	Silt (g/100 g) B	Clay (g/100 g) C	SOM% (g/100 g) D $\frac{\partial\theta}{\partial(\mathrm{SOM})}$	BD (g cm^{-3}) E $\frac{\partial\theta}{\partial(\mathrm{BD})}$
θ_{DUL} (−10 kPa)	0.005018	0.008548	0.008833	0.004966	−0.24230
θ_{DUL} (−33 kPa)	0.003075	0.005886	0.008039	0.002208	−0.14340
θ_{LL} (−1,500 kPa)	−0.000059	0.001142	0.005766	0.002228	0.02671

when soil is tilled, and that changes to the soil water holding characteristics are due only to changes in SOM and the subsequent changes to bulk density. These changes are computed in CSM v4.5 on a daily basis using partial differential analysis based on the Gupta and Larson (1979) relationships:

$$\Delta\theta = \frac{\partial\theta}{\partial(\mathrm{SOM})} \cdot \Delta(\mathrm{SOM}) + \frac{\partial\theta}{\partial(\mathrm{BD})} \cdot \Delta(\mathrm{BD}) \tag{9}$$

where $\Delta\theta$ represents the overall change in water holding limit due to changes in SOM and BD, $\frac{\partial\theta}{\partial(\mathrm{SOM})}$ and $\frac{\partial\theta}{\partial(\mathrm{BD})}$ are the rates of change of θ with respect to SOM and BD; and Δ(SOM) and Δ(BD) are the changes in SOM and BD over a fixed time period. Substituting for the values in Table 3 results in:

$$\Delta\theta = D \cdot \Delta(\mathrm{SOM}) + E \cdot \Delta(\mathrm{BD}) \tag{10}$$

Values of coefficients D and E are listed in Table 3. Then, when a water holding limit is updated, it becomes:

$$\theta' = \theta_0 + \Delta\theta \tag{11}$$

where θ' is the updated water holding limit for either θ_{LL} or θ_{DUL}, and θ_{o} is the corresponding original water holding limit at the reference BD and SOM quantities. The relationship in Eq. 10 uses coefficients for θ_{DUL} corresponding to −10 kPa for coarse soils (sands, loamy sands and sandy loams) and −33 kPa for all other soil textures. Bulk density in CSM v4.5 can also be affected by tillage or compaction; however, these events are assumed not to affect the soil water holding capacity. Only the effects of soil organic matter are considered in the calculations for increasing or decreasing θ_{DUL} and θ_{LL}.

Figure 10 shows the effects of these relationships on plant available water due to the addition of organic matter for three soil texture classes. The plant available water (PAW) in mm^{3}mm^{-3} of water was calculated as:

$$\mathrm{PAW} = \theta_{\mathrm{DUL}} - \theta_{\mathrm{LL}} \tag{12}$$

With an addition of 0.5% organic C to the soil, the plant available water for a clay soil with initial bulk density of 1.05 g cm^{-3} is increased by 0.00033 mm^3 mm^{-3}. For a sandy soil with initial bulk density of 1.55 g cm^{-3}, the plant available water is increased by 0.0134 mm^3 mm^{-3}.

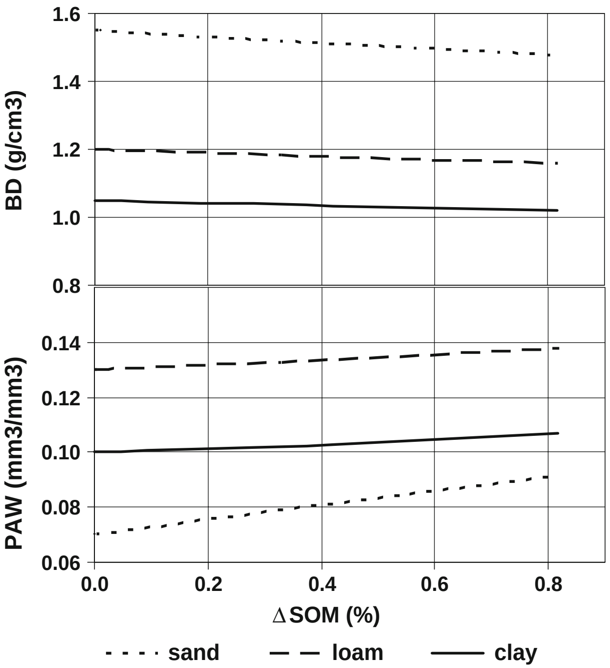

Fig. 10 Change in plant available water (ΔPAW) and bulk density (BD) due to increases in soil organic matter (ΔSOM) for three soil texture classes based on the relationships of Gupta and Larson (1979)

2.4.3 Soil evaporation

A surface mulch layer acts as a sponge, absorbing rainfall and irrigation water and losing water through evaporation. Evaporative demand in CSM is assumed to be met by the mulch layer first, then by the soil. Thus, the mulch layer has the effect of buffering the water content in the upper soil layers, by preventing rapid depletion due to evaporation.

The mulch water balance model adapted for this study was based on CERES-Till (Dadoun 1993) as described by Andales et al. (2000) and modified based on the mulch evaporation routine in the STICS model as described by Scopel et al. (2004). A saturation water content of mulch was shown by Dadoun (1993) to be:

$$\theta_{\mathrm{SATm}} = S_{\mathrm{m}} \cdot M_{\mathrm{mulch}} \cdot 10^{-4} \tag{13}$$

where θ_{SATm} is the water content of the mulch at saturation (mm), M_{mulch} is the mass of surface mulch (kg[dry matter] ha^{-1}) and S_{m} is the saturation water content of surface mulch (kg[H_2O]/kg[dry matter]). Computations of evaporation from the mulch layer make use of the mulch area index (MAI) term (Scopel et al. 2004), calculated as:

$$\mathrm{MAI} = A_{\mathrm{m}} \cdot M_{\mathrm{mulch}} \cdot 10^{5} \tag{14}$$

where A_{m} is the area covered per unit dry weight of residue in cm^2/g. Values for mulch parameters S_{m} and A_{m} in Eqs. 13 and 14 are specified in CSM in an external file and vary depending on the type of surface residues present.

The amount of rainfall or irrigation intercepted by the mulch layer is equal to the difference between the current and saturation water contents of the mulch (θ_{m} and θ_{SATm}). The water absorbed by the mulch layer is reduced by the fractional surface coverage of the mulch (F_c), as described by Andales et al. (2000), and is computed:

$$F_c = 1.0 - \exp(-\mathrm{MAI}) \tag{15}$$

Any water remaining after absorption by surface mulch is available for infiltration into the soil or for runoff.

Potential evaporation from the mulch layer and soil surface layers is related to the energy available at the surface and is reduced in the presence of a crop canopy. The calculation corresponds to a Beer's law equivalent. The potential evaporation from the surface, including both soil and mulch, $\mathrm{EO}_{\mathrm{surf}}$, is:

$$\mathrm{EO}_{\mathrm{surf}} = \mathrm{EO} \cdot \exp(-k_c \cdot \mathrm{LAI}) \tag{16}$$

In Eq. 16, EO is the reference potential evapotranspiration (mm day^{-1}), k_c is the canopy radiation extinction coefficient, and LAI is the leaf area index ($\mathrm{m}^2\ \mathrm{m}^{-2}$). EO is computed in CSM by one of several methods and is modified to account for surface mulch coverage using a weighted average of the albedos from the mulch and the bare soil. The potential evaporation from the mulch layer (EO_{m}, mm day^{-1}) is proportional to the energy received by the mulch after accounting for plant canopy interception and is calculated as:

$$\mathrm{EO}_{\mathrm{m}} = \mathrm{EO}_{\mathrm{surf}} \cdot (1 - \exp(-k_m \cdot \mathrm{MAI})) \tag{17}$$

where k_m is the mulch radiation extinction coefficient. The actual mulch evaporation over the field, E_m, is computed by multiplying by the fractional mulch coverage and is limited to 85% of the total mulch water stored on any given day:

$$E_m = \min[(EO_m), (0.85 \cdot \theta_m)] \cdot F_c \tag{18}$$

Potential soil evaporation, EO_{s}, is then computed as the difference between potential surface evaporation and computed mulch evaporation:

$$\mathrm{EO}_{\mathrm{s}} = \mathrm{EO}_{\mathrm{surf}} - E_{\mathrm{m}} \tag{19}$$

Actual soil evaporation is computed separately in CSM by the method outlined by Ritchie et al. (2009).

2.4.4 Surface water runoff

Bare soils tend to form a crust due to the impact of raindrops on the surface of the soil, thereby reducing the infiltration capacity of the soil. This raindrop action is avoided where there is a protective cover of crop foliage, residues, mulches or even weeds at or over the soil surface (Shaxson and Barber 2003). In this manner a mulch layer will increase the infiltration rate thereby reducing surface water runoff for most storms. In addition to the effects of a higher infiltration rate, a mulch cover can allow increased temporary ponding of water on the surface due to the increased surface roughness thereby allowing more time for infiltration to occur.

CSM v4.5 uses a modified Soil Conservation Service (SCS) Runoff Curve Number method (SCS 1985) to determine quantity of surface runoff on a daily basis. The SCS method assumes an initial abstraction ratio, or the fraction of rainfall that is needed to overcome surface wetting prior to the start of runoff. By increasing the initial abstraction ratio, the effects of increased ponding and increased infiltration rates can be modeled. The initial abstraction is generally expressed as a fraction of potential maximum soil water retention after runoff begins (S, mm), which is computed as a function of the runoff curve number. Under normal conditions, i.e., soil water content close to field capacity, the initial abstraction is about 15% of the potential maximum soil water retention. When a surface mulch layer is present, this initial abstraction ratio is increased linearly from the minimum (i.e., the value used if no mulch is present) to a theoretical maximum value based on the fraction of mulch coverage:

$$r_{\mathrm{IA}} = r_{\mathrm{IA0}} + (r_{\mathrm{MAX}} - r_{\mathrm{IA0}}) \cdot F_c \tag{20}$$

where r_{IA0} and r_{IA} are the initial abstraction ratios with no mulch cover and after adjusting for mulch cover, respectively, r_{MAX} is the theoretical maximum initial abstraction ratio at 100% mulch cover and F_c is the fractional mulch coverage as computed in Eq. 15. An r_{MAX} of 0.6, for example, means that with 100% surface mulch coverage, runoff would not occur until rainfall had exceeded 60% of the maximum soil retention, thereby significantly decreasing total seasonal runoff from a field.

Substitution into the SCS runoff curve number equation (SCS 1985) yields:

$$\mathrm{RO} = \frac{(P - r_{\mathrm{IA}} \cdot S)^2}{P + (1 - r_{\mathrm{IA}}) \cdot S} \tag{21}$$

where RO and P are surface runoff and rainfall in mm.

The approach outlined above was tested and calibrated in the DSSAT-CSM by simulating the seasonal runoff for a hypothetical maize experiment using seven application rates of mulch ranging from 500 kg ha^{-1} (10% surface coverage) to 15,000 kg ha^{-1} (90% surface coverage). Results of these simulations are presented in Fig. 11. The site data for the simulations were from a field experiment conducted by Bowen et al. (1993) in central Brazil on a clay loam soil with a seasonal rainfall of 1,089 mm. The simulations resulted in a series of seasonal runoff values expressed as fractions of the runoff that would occur with no mulch cover.

Quantitative analyses of the effects of a mulch cover on surface runoff have been presented by Scopel et al. (2004) for sites in Brazil and Mexico and by Lal (1976, 1995) for sites in western Nigeria over two seasons. These data are graphed with the results from the DSSAT-CSM simulations in Fig. 11. A value of $r_{\mathrm{MAX}} = 0.6$ (Eq. 20) resulted in simulated values which matched extremely well with those measured in the Scopel et al. (2004) experiments. The data measured by Lal (1995) provided further validation for the method and its applicability under various mulch coverage fractions.

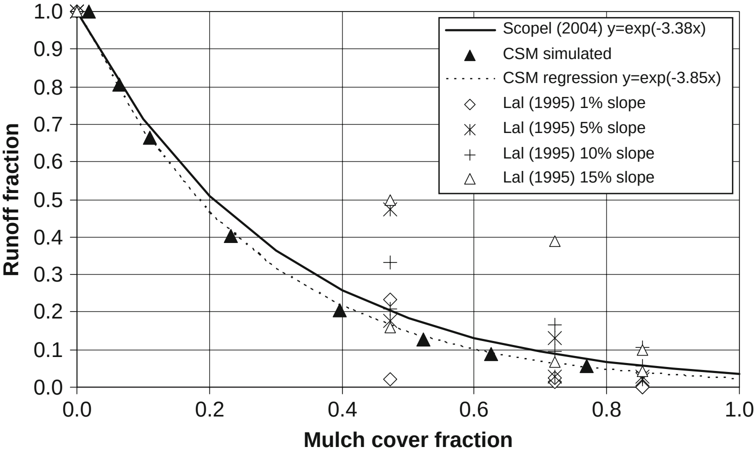

Fig. 11 Reduction of surface runoff due to mulch cover as a function of the fraction of mulch coverage. Simulated DSSAT-CSM values are for a hypothetical maize experiment on a silty clay in Brazil (Bowen et al. 1993). The Scopel regression equation and Lal data are from measurements in Brazil and Mexico (Scopel et al. 2004) and Africa (Lal 1976, 1995)

3 Sensitivity analysis

In order to assess the relative importance of various soil carbon-related input variables on selected model outputs, a global sensitivity analysis was performed. The sensitivity analysis of a crop model is analogous to an experiment where measured data from nature are being replaced by the simulated crop model results (Monod et al. 2006). The classical theory of experimental design provides very useful tools for sensitivity analysis, including factorial designs, which allow simultaneous evaluation of the influence of many factors with a limited number of simulations. The sensitivity of the DSSAT-CENTURY model outputs to various input parameters was evaluated using a factorial design method.

3.1 Methods

The objective of this sensitivity analysis was to evaluate the response of the DSSAT-CENTURY model to changes in input parameters. Each experiment included a simulation of a hypothetical 11-year maize-fallow rotation. Weather data consisted of 10 years of observed daily values for rainfall, maximum and minimum temperature and solar radiation for Gainesville, Florida, years 1978 through 1987. The simulations included an 11th year in which the 1978 weather data were repeated to evaluate the differences in simulated values due to changes in soil conditions over the preceding 10-year period under the same weather that occurred in year 1. Thus, the differences in simulated response variables between year 11 and year 1 are attributed only to differences in soil physical and chemical characteristics.

Six simulated dependent variables were selected for evaluation of their responses to input factors:

1. "Yield", the average yield for 10 years of measured weather data (kg ha^{-1});
2. "Yield difference", the difference in yield between the first and 11th year of simulation, both which use 1978 weather observations (kg ha^{-1});
3. "Water productivity", the 10-year average value of water productivity, defined as yield per seasonal evapotranspiration rate (kg[dry matter] ha^{-1} mm[ET]$^{-1}$);
4. "N leached", the 10-year average seasonal nitrogen leached from the field (kg[N] ha^{-1});
5. "N mineralized", the 10-year average quantity of inorganic nitrogen released to the soil as a result of the decomposition of organic matter (kg[N] ha^{-1}); and
6. "OC difference", the difference in organic matter content in the top 20 cm of soil over the 10 year simulation (g[C]/100 g[soil]).

The analysis was not intended to evaluate the entire DSSAT-CSM model, but rather a portion of the model dealing with organic matter accumulation and depletion and therefore the independent variables of interest are limited to those that contribute to the accumulation or depletion of organic matter in the soil or on the surface. Seven independent variables, or factors, were used in the factorial design, as listed in Table 4. These variables represent either initial conditions (SOIL, OC, SOM) or management operations (FERT, TILL, IR and HR) and each has been discussed previously in this document with respect to modeling its effects on organic matter dynamics. Each of the factors has two input levels or values, except

Table 4 Independent factors used in the sensitivity analysis

Factors	Factor ID	Values used in sensitivity analysis
Soil type	SOIL	Millhopper fine sand
		Tifton sandy loam
Initial organic carbon	OC	Low C value from range for specified soil type (%) (0.20% for Millhopper, 0.35% for Tifton soils in top 20 cm)
		High C value from range for specified soil type (%) (0.50% for Millhopper, 0.74% for Tifton soils in top 20 cm)
Initial stable organic carbon	SOM	High proportion of stable C (low fertility) expressed as a proportion of total SOM (SOM3 = 90% of total SOM)
		Lower proportion of stable C (higher fertility) (SOM3 = 40% of total SOM)
Fertilizer application rate	FERT	No Fertilizer
		Moderate fertilizer application rate (116 kg[N] ha^{-1})
		High fertilizer application rate (400 kg[N] ha^{-1})
Tillage	TILL	No tillage
		Tillage operations at planting and harvest
Irrigation	IR	Rainfed (no irrigation)
		Automatic irrigation as needed
Harvest residue	HR	All surface residues removed from field
		All surface residues left in field after harvest

FERT, which has three values, resulting in a total of 192 simulations, representing all combinations of these input factors.

A simulation was performed for each of the factorial treatments using the hypothetical 11-year maize-fallow rotation. The results of the simulations were analyzed using SAS® software (SAS v9.1. ©2002–2003). The GLM procedure was the algorithm used to obtain the sums of squares for the main effects of each of the seven factors, as well as the effects of interactions of combinations of up to three factors for each of the six dependent variables.

The total model sensitivity to the factors, in terms of sums of squares variability, was decomposed into variability due to individual factors and their interactions:

$$\mathrm{SS}_T = \sum_{i}^{S} \mathrm{SS}_i + \sum_{i<j} \mathrm{SS}_{ij} + \cdots + \mathrm{SS}_{1\ldots S} \tag{22}$$

where SS_T is the total sum of squares variability in a particular model response. SS_i is the sum of squares associated with the main effect of independent variable i; SS_{ij} is the sum of squares associated with the interaction between independent variables i and j; and s is the number of independent variables. Interactions of up to three independent factors were included in the computation of total effect.

Sensitivity indices that represented the relative contribution of each of the factorial terms to the total variability were computed by dividing each term on the right of Eq. 22 by the total sum of squares. The main effects sensitivity indices, $\mathrm{Si} = \frac{SSi}{\mathrm{SS}_T}$, represent the direct effect of each factor on model responses. The interaction sensitivity indices represent the contribution of combinations of variables, in this analysis limited to interactions of two $\left(S_{ij} = \frac{\mathrm{SS}_{ij}}{\mathrm{SS}_T}\right)$ or three $\left(S_{ijk} = \frac{\mathrm{SS}_{ijk}}{\mathrm{SS}_T}\right)$ variables. Total sensitivity indices, such as $\mathrm{TS}_1 = \frac{\mathrm{SS}_1+\mathrm{SS}_{12}+\mathrm{SS}_{13}+\mathrm{SS}_{123}}{\mathrm{SS}_T}$ for factor 1 and $s = 3$, summarize the total influence of a particular factor on a particular model response and in this analysis include the effects of interactions of up to three factors.

A second factorial analysis was performed that excluded the effects of fertilizer and irrigation applications in order to assess the sensitivities of simulated responses under rainfed, low input management systems that are typical in many agricultural areas of the world. This second analysis consisted of five factors (SOIL, OC, SOM, TILL, and HR) each with two levels, resulting in a 32-member subset of the full 192 experiments.

In addition to the 192 simulated experiments, a simulation was performed to obtain the potential yield or the production which is not limited by water or nutrient deficiencies or other chemical or biological stressors. This theoretical maximum yield for each weather year provided a reference point for comparison with reduced yields simulated in the factorial experiments.

3.2 Results

The simulations using the 192 factorial treatments resulted in a wide range of maize crop yields and other dependant variables, as summarized in Table 5. Figure 12 shows the 11-year time series of yields simulated for Tifton sandy loam soils

Table 5 Summary statistics for the 6 dependent response variables for 192 simulations

Dependent variable	Mean	Std dev	Min value	Max value	Skewness
Yield (kg ha^{-1})	5,607	4,379	72	14,322	0.652
Yield difference (kg ha^{-1})	−1,104	1,856	−9,144	769	−1.994
Water productivity (kg[dry matter] ha^{-1} mm[ET]$^{-1}$)	13.20	8.28	0.38	29.54	0.252
N leached (kg[N] ha^{-1})	190.8	127.8	37.9	532.7	0.882
N mineralized (kg[N] ha^{-1})	233.5	126.5	49.2	602.2	0.583
OC difference (g[C]/100 g[soil])	−0.112	0.114	−0.375	0.065	−0.844

(one level of the factor, SOIL) for four selected levels of the management operations factors, plus the simulated potential yield. The simulated yield for the irrigated, fertilized and high organic matter combination, treatment (b) on Fig. 12, approached the potential production, treatment (a). Simulated yields were reduced as fertilizer, and then irrigation, and then organic matter, treatments (c), (d) and (e) were reduced or removed from the treatments.

Figure 13 shows the amount of soil organic matter simulated over time for other treatment combinations with varying initial soil carbon and initial fraction of stable organic matter. Treatment (b), with high initial organic C and a high fraction of decomposable organic matter (SOM2), resulted in a rapid decrease in organic matter over the simulation period, while treatment (c), with low initial organic matter and a low decomposable fraction, resulted in very little decomposition. Although not shown on Fig. 13, fertilizer, irrigation, and tillage did not have as great an effect on changes to organic carbon over time as did the initial organic carbon and soil type.

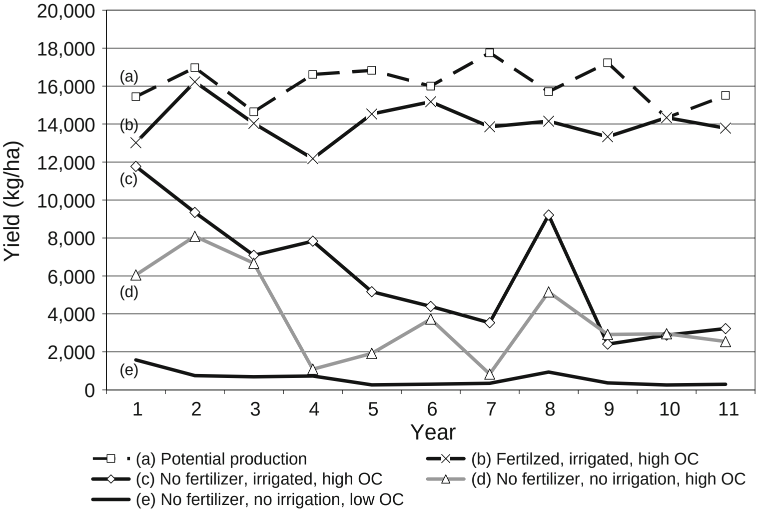

Fig. 12 Time series of maize yields over 11 year simulation period for four management operations and potential production, all of which illustrate the range of simulated values for a Tifton sandy loam soil with no tillage

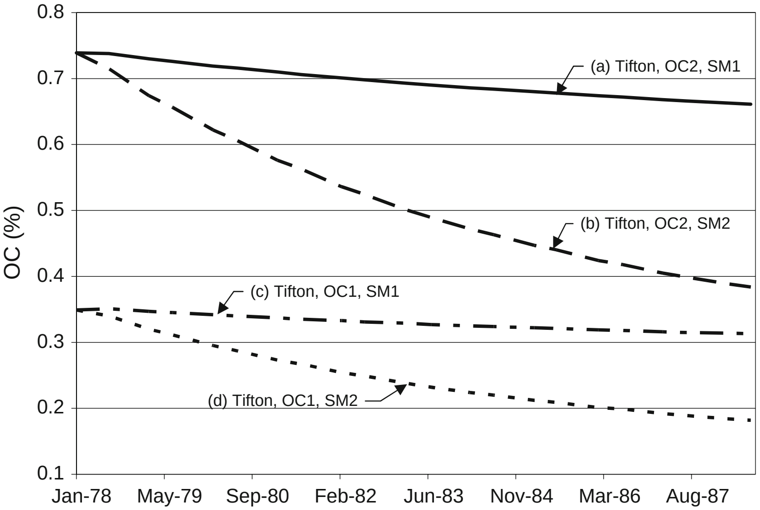

Fig. 13 Time series showing organic carbon in the top 20 cm of soil over time for Tifton loamy sands with two initial organic matter contents (OC1 = 0.35% and OC2 = 0.74%) and two initial stable organic matter fractions (SM1 = 90%, SM2 = 40%). All four treatments included zero fertilizer and irrigation, no tillage and no harvest residues left in the field

The results of the sensitivity analyses are summarized in Fig. 14 for the full set of 192 treatments. The graphs present the single factor (or main effect) and total sensitivities of the six model outputs to the seven factors, including interactions of up to three factors. The two yield response variables, “Yield” and “Water productivity”, had the highest responses to fertilizer, irrigation, soil type and initial organic carbon, in that order. Because the weather data used for year 11 was the same as for year 1, the difference in yield between year 11 and year 1 (“Yield difference” on Fig. 14), demonstrates the decline in soil fertility after 10 years of crop rotation. The quantity of soil organic matter has a much greater influence on this “Yield difference” variable than on the ten-year average production variable, “Yield”.

The two nitrogen variables analyzed, “N leached” and “N mineralized”, were highly sensitive to the initial organic matter factor, although fertilizer application rate was the primary factor influencing “N leached”. The sensitivities to tillage were small for all of the model outputs relative to their sensitivities to the other factors.

Figure 14 shows how dominant the effects of irrigation and fertilizer management factors are on grain yield and biomass relative to the other factors. High yields were possible with high fertilizer use and irrigation regardless of soil type and organic matter, for instance. However, organic matter and stable organic carbon fractions were important factors affecting quantities of N mineralized and leached and changes in soil organic carbon after 10 years. By eliminating the fertilizer and irrigation factors in order to study model sensitivities under rainfed, low input management, the sensitivities to organic carbon and stable carbon fraction become

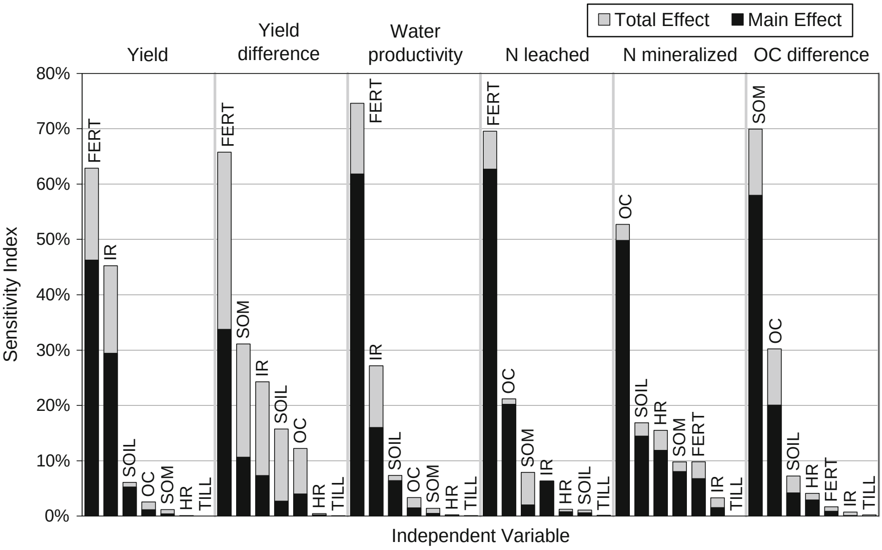

Fig. 14 Sensitivity indices for six simulated response variables computed from 192 experiments using seven factors including fertilizer and irrigation. The main effect sensitivity index represents the direct effect of a factor on a model response. The total effect represents the main effect plus interactions of up to two other factors

dominant as shown in Fig. 15, which summarizes the 32-treatment subset which includes only non-irrigated and non-fertilized treatments. This figure indicates that crops grown without irrigation or fertilizer under these environmental conditions would be strongly influenced by soil type, initial soil carbon and its stable fraction. This is especially true relative to the change in soil organic carbon over time. These results show that the sustainability of soil productivity is strongly affected by soil type, initial soil carbon and its stable fraction. This is shown by the dominance of the two soil carbon factors (SOM and OC) on “Yield difference” 10 years after the first crop for the rainfed, non-fertilized treatments.

4 Summary

The DSSAT-CENTURY soil organic matter module was incorporated into the DSSAT-CSM in order to more adequately model the dynamics of organic carbon and nutrient cycling and the concomitant effects on soil properties and processes. This additional capability required additional inputs from existing modules and also provided an opportunity to improve the simulation capability of other extant modules.

The increased complexity of the new soil organic matter module required additional input data both to establish initial conditions for the system as well as to define process rates and limits throughout the model. Some of the additional input data are difficult for users to obtain, such as organic carbon fractions. A hierarchical

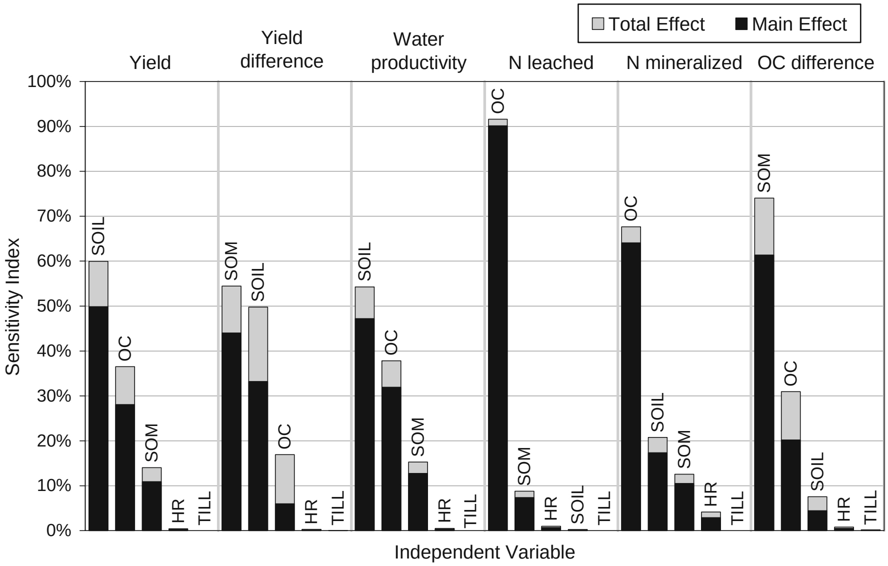

Fig. 15 Sensitivity indices for six simulated variables computed from 32 experiments for five selected factors. Only non-fertilized and non-irrigated combinations were simulated. The main effect sensitivity index represents the direct effect of a factor on a model response. The total effect represents the main effect plus interactions of up to two other factors

structure was established for estimating needed input conditions based on data that are available.

Quantities of senesced plant tissue and crop residues left in the field after harvest were required from the various plant growth modules, as well as the composition of these additions of organic matter. These quantities are particularly critical for long-term simulations where the accumulation or depletion of organic matter can be of primary importance to the fertility of the cropping system. Some of these changes were handled in a generic way to minimize coding redundancies between the existing crop modules and any future addition of new crop modules to the model.

The ability to model in greater detail the dynamics of organic matter provided opportunities to improve existing capabilities in the model. Some of these improvements required no additional modifications to the model, such as inorganic nitrogen and phosphorus modeling as impacted by the improved mineralization and immobilization predictions. Other modeling improvements required modification of existing modules, such as the changes to soil properties affecting water holding capacity as a function of soil organic matter, and the effects of a surface mulch cover on soil evaporation and surface water runoff.

The sensitivity of the DSSAT-CENTURY module to various input parameters and conditions was evaluated using a factorial design and sensitivity analysis procedure. The analysis indicated that the yield outputs were far more influenced by management practices than by organic matter inputs for systems which included good irrigation and nutrient management practices. Simulated leaching and mineralization of nitrogen were more sensitive to soil properties and initial organic carbon. However, if the crops were rainfed and not fertilized, as in many production situations in developing countries, the soil carbon content and its stable fraction were dominant factors affecting yield, soil carbon dynamics, N mineralization and leaching, and sustainability of yield after 10 years of production.

The difficulties encountered in implementing a more complex component into an existing modular model were demonstrated by the required model modifications beyond the addition of only the soil organic matter module, if the full capabilities of the new module are to be utilized. Similar challenges can be anticipated with the addition of other complex modules such as pest and disease damage.

Acknowledgments This paper was partially supported by the Office of Natural Resources Management and Office of Agriculture in the Economic Growth, Agriculture, and Trade Bureau of the U.S. Agency for International Development, under terms of Grant No. LAG-G-00-97-00002-00.

References

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

Adiku SGK, Narh S, Jones JW, Laryea KB, Dowuona GN (2008) Short-term effects of crop rotation, residue management, and soil water on carbon mineralization in a tropical cropping system. Plant Soil 311:29–38

Andales AA, Batchelor WD, Anderson CE, Farnham DE, Whigham DK (2000) Incorporating tillage effects into a soybean model. Agric Syst 66:69–98

Bado BV, Sedogo MP, Lompo F, Bationo A (2004) Long-term effects of crop rotations and fertilizer applications on soil organic carbon, N recovery, soil properties and crop yields in Soudanian and Guinean zones of West Africa. Regional Scientific Workshop on Land Management for Carbon Sequestration, Bamako, Mali, 26–27 February 2004

Battacharyya T, Chandran P, Ray SK, Mandal C, Pal DK, Venugopalan MV, Durge SL, Srivastava P, Dubey PN, Kamble GK, Sharma RP, Wani SP, Rego TJ, Pathak P, Ramesh V, Manna MC, Sahrawat KL (2007) Physical and chemical properties of selected benchmark spots for carbon sequestration studies in semi-arid tropics of India. Global Theme on Agroecosystems Report no. 35. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India; and Indian Council of Agricultural Research (ICAR), New Delhi, India, 236 pp

Boote KJ, Jones JW, Mishoe JW, Berger RD (1983) Coupling pests to crop growth simulators to predict yield reductions. Phytopathology 73(11):1581–1587

Bostick WM, Bado BV, Bationo A, Tojo Soler C, Hoogenboom G, Jones JW (2006) Soil carbon dynamics and crop residue yields of cropping systems in the Northern Guinea Savanna of Burkina Faso. Soil Tillage Res 93:138–151

Bouman BAM, Van Keulen H, Van Laar HH, Rabbinge R (1996) The 'School of De Wit' crop growth simulation models: a pedigree and historical overview. Agric Syst 52:171–198

Bowen WT, Jones JW, Carsky RJ, Quintana JO (1993) Evaluation of the nitrogen submodel of CERES-Maize following legume green manure incorporation. Agron J 85(1):153–159

Brisson N, Gary C, Justes E, Roche R, Mary B, Ripoche D, Zimmer D, Sierra J, Bertuzzi P, Burger P, Bussière F, Cabidoche YM, Cellier P, Debaeke P, Gaudillère JP, Hénault C, Maraux F, Seguin B, Sinoquet H (2003) An overview of the crop model STICS. Eur J Agron 18:309–332

Dadoun FA (1993) Modeling tillage effects on soil physical properties and maize (*Zea mays*, L.) development and growth. Unpublished PhD thesis, Michigan State University, MI

De Wit CT, Goudriaan J (1974) Simulation of ecological processes. Simulation monographs, Pudoc, Wageningen, 159 pp

De Wit CT, Goudriaan J, Van Laar HH, Penning de Vries FWT, Rabbinge R, Van Keulen H, Louwerse W, Sibma L, De Jonge C (1978) Simulation of assimilation, respiration and transpiration of crops. Simulation Monographs, Pudoc, Wageningen, 148 pp

Duxbury JM (2006) Develop practical methods to measure gains and losses of soil organic C over time in spatially variable soils in South Asia: development of soil C-texture relationships. In: Soil Management Collaborative Research Support Program, Project Year 9 annual progress report. Tropical Plant & Soil Sciences Department, University of Hawaii., pp 59–60. http://tpss.hawaii.edu/sm-crsp/pubs/pdf/AR9_FinalReport.pdf

FAO (Food and Agriculture Organization of the United Nations) (2004) Assessing carbon stocks and modelling win-win scenarios of carbon sequestration through land-use changes. FAO, Rome, Italy, 156 pp. ISBN 92-5-105168-5

Gijsman AJ, Hoogenboom G, Parton WJ, Kerridge PC (2002) Modifying DSSAT crop models for low-input agricultural systems using a soil organic matter-residue module from CENTURY. Agron J 94:462–474

Godwin DC, Singh U et al (1998) Nitrogen balance and crop response to nitrogen in upland and lowland cropping systems. In: Tsuji GY et al (eds) Understanding options for agricultural production. System approaches for sustainable agricultural development. Kluwer Academic Publishers, Dordrecht, pp 55–77

Gupta SC, Larson WE (1979) Estimating soil water retention characteristics from particle size distribution, organic matter content and bulk density. Water Resour Res 15(6):1633–1635

Hoogenboom G, Jones JW, Wilkens PW, Porter CH, Batchelor WD, Hunt LA, Boote KJ, Singh U, Uryasev O, Bowen WT, Gijsman AJ, du Toit AS, White JW, Tsuji GY (2004) Decision Support System for Agrotechnology Transfer Version 4.0 [CD-ROM]. University of Hawaii, Honolulu

Hoogenboom G, Jones JW, Wilkens PW, Porter CH, Hunt LA, Boote KJ, Singh U, Uryasev O, Lizaso JI, Gijsman AJ, White JW, Batchelor WD, Tsuji GY (2009) Decision Support System for Agrotechnology Transfer Version 4.5 [CD-ROM]. University of Hawaii, Honolulu

Izaurralde RC, Williams JR, McGill WB, Rosenberg NJ, Quiroga Jakas MC (2006) Simulating soil C dynamics with EPIC: model description and testing against long-term data. Ecol Modell 192:362–384

Jenkinson DS, Rayner JH (1977) Turnover of soil organic-matter in some of Rothamsted classical experiments. Soil Sci 123:298–305

Jenkinson DS, Hart PBS, Rayner JH, Parry LC (1987) Modelling the turnover of organic matter in long-term experiments at Rothamsted. INTECOL Bull 15:1–8

Jones JW, Keating BA, Porter CH (2001) Approaches to modular model development. Agric Syst 70:421–443

Jones JW, Hoogenboom G, Porter CH, Boote KJ, Batchelor WD, Hunt LA, Wilkens PW, Singh U, Gijsman AJ, Ritchie JT (2003) The DSSAT cropping system model. Eur J Agron 18:235–265

Keating BA, Carberry PS, Hammer GL, Probert ME, Robertson MJ, Holzworth D, Huth NI, Hargreaves JNG, Meinke H, Hochman Z, McLean G, Verburg K, Snow V, Dimes JP, Silburn M, Wang E, Brown S, Bristow KL, Asseng S, Chapman S, McCown RL, Freebairn DM, Smith CJ (2003) An overview of APSIM, a model designed for farming systems simulation. Eur J Agron 18:267–288

Kiem R (2002) Characterization of refractory soil organic matter in long term agroecosystem experiments. PhD Thesis, Lehrstuhl fuer Bodekunde, Technische Universität München, Germany, 184 pp

Koo J (2007) Estimating Soil Carbon Sequestration in Ghana. PhD Dissertation, Agricultural and Biological Engineering Department, University of Florida, Gainesville, FL, pp 198

Lal R (1976) Soil erosion problems on Alfisols in western Nigeria and their control. International Institute of Tropical Agriculture (IITA) Monograph 1, 208 pp

Lal R (1995) Sustainable management of soil resources in the humid tropics. United Nations University Press. Tokyo. http://www.unu.edu/unupress/unupbooks/uu27se/uu27se00.htm

Lal R (2007) Carbon management in agricultural soils. Mitig Adapt Strateg Glob Change 12:303–322

Lloyd J, Taylor JA (1994) On the temperature dependence of soil respiration. Funct Ecol 8:315–323

Lobe I, Amelung W, Du Preez CC (2001) Losses of carbon and nitrogen with prolonged arable cropping from sandy soils of the South African Highveld. Eur J Soil Sci 52:93–101

McCown RL, Hammer GL, Hargreaves JNG, Holzworth DP, Freebairn DM (1996) APSIM: a novel software system for model development, model testing, and simulation in agricultural systems research. Agric Syst 50:255–271

McGill WB (1996) Review and classification of ten soil organic matter (SOM) models. In: Powslon DS, Smith P, Smith JU (eds) Evaluation of soil organic matter models using existing long-term datasets. NATO ASI Series I, vol 38. Springer-Verlag, Heidelberg, pp 111–132

Monod H, Naud C, Makowski D (2006) Chapter 3. Uncertainty and sensitivity analysis for crop models. In: Wallach D, Makowski D, Jones JW (eds) Working with dynamic crop models; evaluation, analysis, parameterization, and applications. Elsevier B.V, Amsterdam

Parton WJ, Schimel DS, Cole CV, Ojima DS (1987) Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Sci Soc Am J 51:1173–1179

Parton WJ, Stewart JWB, Cole CV (1988) Dynamics of C, N, P and S in grassland soils: a model. Biogeochemistry 5:109–131

Parton WJ, McKeown B, Kirchner V, Ojima DS (1992) CENTURY users manual. Colorado State University, NREL Publication, Fort Collins

Parton WJ, Ojima DS, Cole CV, Schimel DS (1994) A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. In: Bryant RB, Arnold RW (eds) Quantitative modeling of soil forming processes. Soil Science Society of America, Special Publication No. 39, Madison, WI, pp 147–167

Porter C, Jones JW, Braga R (2000) An approach for modular crop model development. International Consortium for Agricultural Systems Applications, Honolulu, HI, p 13. Available from http://icasa.net/modular/index.html

Ritchie JT, Porter CH, Judge J, Jones JW, Suleiman AA (2009) Extension of an existing model for soil water evaporation and redistribution under high water content conditions. Soil Sci Soc Am J 73:792–801

Scopel E, Da Silva FAM, Corbeels M, Affholder F, Maraux F (2004) Modelling crop residue mulching effects on water use and production of maize under semi-arid and humid tropical conditions. Agronomie 24:383–395

SCS (Soil Conservation Service) (1985) National Engineering Handbook Section 4: hydrology. U.S. Department of Agriculture, Washington

Shaxson F, Barber R (2003) Optimizing soil moisture for plant production, the significance of soil porosity. Food & Agriculture Organization Soils Bulletin 79. FAO, Rome

Smith P, Smith JU, Powlson DS, McGill WB, Arah JRM, Chertov OG, Coleman K, Franko U, Frolking S, Jenkinson DS, Jensen LS, Kelly RH, Klein-Gunnewiek H, Komarov AS, Li C, Molina JAE, Mueller T, Parton WJ, Thornley JHM, Whitmore AP (1997) A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. Geoderma 81:153–225

Tsuji GY, Uehara G, Balas S (eds) (1994) Decision Support System for Agrotechnology Transfer (DSSAT) Version 3. University of Hawaii, Honolulu

Van Ittersum MK, Leffelaar PA, Van Keulen H, Kropff MJ, Bastiaans L, Goudriaan J (2003) On approaches and applications of the Wageningen crop models. Eur J Agron 18:201–234

Zhao L, Sun Y, Zhang X, Yang X, Drury CF (2006) Soil organic carbon in clay and silt-sized particles in Chinese mollisols: relationship to the predicted capacity. Geoderma 132:315–323

Zinn LY, Lal R, Bigham JM, Resck DVS (2007) Edaphic controls on soil organic carbon retention on Brazilian Cerrado: texture and mineralogy. Soil Sci Soc Am J 71:1204–1214