Procedures for Initializing Soil Organic Carbon Pools in the DSSAT-CENTURY Model for Agricultural Systems

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Process-based soil organic C (SOC) models are widely used for simulating, monitoring, and verifying soil C change. In such models, determining the initial distribution of SOC across multiple pools is often not well defined, yet pool initialization can strongly influence the subsequent SOC dynamics. We developed a model-based procedure to initialize SOC fractions that uses site-specific soil, climatic, and land use history information, along with measured initial total SOC, to estimate SOC distribution across pools. The procedure consists of creating sets of SOC fractions for scenarios including different field histories, soil texture, and management practices for medium- and long-term simulations to provide a broad spectrum of conditions, using data from an experimental site in Georgia. Tables created using this procedure can help model users select the SOC fractions needed to properly initialize the model. The model is executed for the duration of the prior land use history time period, and the simulated final total SOC is compared with the soil C measurement at the beginning of the subsequent experimental time period. If these values are equal, the final SOC fractions from the land use history simulations are used with the measured soil C to start the simulation of the cropping system being studied. If these values are not equal, then the procedure is repeated iteratively until the measured value of soil C is adequately predicted. We demonstrated the improved prediction accuracy by using the proposed procedure in simulating soil C for a long-term field experiment in Michigan.

Abbreviations: CTOT, total soil organic carbon; KBS, Kellogg Biological Station; SOC, soil organic carbon.

Soil organic C is recognized as a heterogeneous mixture of organic substances, but for experimental and modeling purposes it is often conceptually divided into discrete C pools for interpretation of decomposition kinetics, chemical and physical attributes (e.g., C/N ratios or solubility), and stabilization mechanisms (Jenkinson, 1981; Elliott et al., 1996). The SOC pools or fractions have been determined by many different procedures (Olk and Gregorich, 2006). Chemical-based extractions were dominant until recent decades, when physically based fractionations have become increasingly popular, and more elaborate analyses for microbial characteristics have been developed. Comprehensive reviews are available for extractions involving particulate organic matter and the light fraction (von Lützow et al., 2007; Gregorich and Janzen, 1996; Wander, 2004), particle size fractions, aggregate classes (Six et al., 2004), and chemical extractants (Hayes, 1985; Stevenson, 1994). In addition, SOC pool differentiation has also been attempted on the basis of mid-infrared spectra (Janik et al., 2007). At present, however, there is no single, agreed-on biological, physical, or chemical fractionation technique that adequately describes the continuum of SOC from the standpoint of decomposition and stabilization kinetics.

Process-based SOC models are widely used for simulating, monitoring, and verifying soil C change. Modeling is a necessary tool for extrapolating the findings on C changes obtained from individual experiments to larger areas or regions and varying time scales to assess future changes (Paustian et al., 1997; Falloon et al., 2002; Senthilkumar et al., 2009; Ogle et al., 2010). To extend models beyond a single field plot (e.g., a well characterized experimental field), a number of soil, plant, climate, and management-related parameters and driving variables are needed that

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span the range of spatial and temporal conditions being considered (Paustian et al., 1995). Predicted changes in SOC should also be compared with measured data that represent the spatial and temporal range of model inferences to assess uncertainty and bias (Falloon and Smith, 2003; Ogle et al., 2007).

Models can be used to gain an understanding of the processes and control involved in nutrient cycles and to generate data on the size of various pools and the rates at which nutrients are transformed. Most models of SOC dynamics include multiple pools or fractions of soil C that are governed by first-order decay rates (Paustian, 1994; McGill, 1996; Falloon and Smith, 2000). These models begin by modeling the decay of litter at the soil surface.

The division of SOM into various pools is based on various criteria such as stabilization mechanisms, bioavailability, and kinetic parameters. Aside from litter pools, several models subdivide SOC into three main pools: active, slow, and resistant (van Veen and Paul, 1981; van Veen et al., 1984; Parton et al., 1988a). The active pool is characterized by a rapid turnover rate, while the larger size pools have a turnover rate that ranges from a few decades (the slow pool) to thousands of years (the resistant pool). The active pool is associated with measureable entities such as microbial biomass, while the slow and resistant pools are more conceptual (Plante and Parton, 2007).

A particular challenge for regional model applications is to derive estimates for the initial SOC conditions (i.e., attributes at the start of the simulation). The importance of initializing different pools of C has not been emphasized enough, especially in agricultural systems in which crops depend on nutrients mineralized from organic matter and in which land use and management practices change frequently with time. The availability of reliable measurements of total SOC may not be sufficient to properly initialize soil C models. Depending on the partitioning of soil C into the different pools, decomposition of SOC during a growing season may result in very low or very rapid rates of mineralization and supply of nutrients. Thus, for the same initial total SOC value, the model may simulate vastly different yields under identical environmental and management conditions depending on how the SOC is partitioned into different pools. Typical values of the C fractions in each pool may be provided by model developers, but caution should be used because such information may prove to be unreliable for the soil and cropping system being simulated. In early attempts to initialize the DSSAT-CENTURY model to simulate soil C dynamics and crop production in Africa, Bostick et al. (2007) found that neither crop yield nor soil C dynamics were adequately described. The simulated yields, soil C loss, and N uptake were typically higher than those measured in crop rotation experiments, such as in an 11-yr study in Burkina Faso (Bado, 2002). Simulated mineralization of N from soil organic matter provided relatively high amounts of N, whereas in reality, the crop growth was severely limited by a lack of N. Such inconsistency may be due to the fact that the DSSAT-CENTURY model was implemented with two default SOC fractions that varied only as a function of prior land use (grassland or cultivated soils) (Gijsman et al., 2002).

A common approach to initializing soil C pools in dynamic SOC models is based on the use of soil C steady-state conditions, obtained by simulating a long time period of 100 to 10,000 yr (Parton et al., 1988b). One of the limitations of this method is that agricultural systems often change during a relatively short period of time (i.e., every 3–10 yr), which does not allow the soil C levels to reach steady state. A preliminary sensitivity analysis of initial SOC pool size and mineralization using the DSSAT-CENTURY model clearly demonstrated that the initial partitioning of measured soil C into pools using reported "typical" values was inadequate for production systems with little or no external nutrient inputs. An additional set of analyses showed that initializing the soil C pool fractions using long-term simulations (i.e., >1000 yr) after achieving steady state was also inadequate (J.W. Jones, personal communication, 2010).

The literature on this important issue is limited, even though it is well known and accepted that model initializations can influence the behavior of soil organic C dynamics. Conceptual model pools in many cases do not correspond to measurable fractions (Smith et al., 2002) and thus the initial conditions for individual pools cannot be directly determined from measurements. The inappropriate initialization of SOC pools can also lead to inaccurate assessment of interannual variability (Yeluripati et al., 2009). In addition to the conventional procedure of spin-up simulation for hundreds or thousands of years to find a soil C equilibrium or assume the equilibrium conditions, recently Yeluripati et al. (2009) assessed the potential of Bayesian calibration to initialize soil C pools and reduced the uncertainties in the initial C distribution. This methodology overcomes some of the difficulties with the long-term spin-up but it is computationally intensive. Even though the Bayesian procedure was tested with some CO_2 measurements—the temporal variability associated with CO_2 output within and between days—it did not provide a comprehensive test of the initialization of pools for predicting longer term SOC dynamics in agricultural systems.

In this study, we hypothesized that initial SOC pools in the model can be estimated if total SOC and soil texture are measured and the cropping history is known. Precise initialization of SOC fractions by simulating the past cropping history at a site allows a better comparison of measured and estimated SOC trends. Large relative differences in fraction sizes may occur in response to field management history even if the total SOC is the same at Time 0 for a given soil. The primary objective of this study was to develop a model-based procedure to initialize SOC fractions that would closely match the measured value of SOC using site-specific soil, climatic, and land management conditions. The procedure produces initialization data sets of SOC fractions for a wide range of scenarios that take into account site agronomic history, soil texture, and climate to accommodate a broad spectrum of conditions. We further aimed to demonstrate the improved accuracy obtained using the proposed procedure in simulating SOC for an experimental site in Michigan.

METHODS AND PROCEDURES

Model Description

The DSSAT-CENTURY model was developed by Gijsman et al. (2002) by incorporating the widely used CENTURY model with the DSSAT cropping system model (Hoogenboom et al., 2004). The CENTURY model (Parton et al., 1987, 1988a; Parton and Rasmussen, 1994; Metherell et al., 1993) is an ecosystem biogeochemistry model that simulates the dynamics of soil organic C and N for a homogeneous land area. The DSSAT-CENTURY model calculates the initial amount of organic C (kg ha^{-1}) in each pool using initial SOC fractions, bulk density, and the thickness of soil layers (Gijsman et al., 2002). The model has three SOC pools (active, intermediate, and passive) in each of several soil layers, above- and belowground litter pools, and a surface microbial C pool that is associated with decomposing surface litter. The pools are conceptually defined (i.e., they don't correspond directly to a specific measured SOC pool), in which the decomposition rate constants and other parameters affecting decay and stabilization processes have been estimated from long-term field experiments and laboratory incubations (Parton et al., 1987, 1988b). The daily total C change per layer is determined from the amount of C in each pool, a decomposition factor calculated as a function of soil temperature and water content, the maximum specific decomposition rate for each pool, and a cultivation factor that affects the mineralization process.

The active pool (SOC1) in CENTURY, including DSSAT-CENTURY (Gijsman et al., 2002), represents soil microbes and microbial products. It has a turnover time of a few months, depending on the environment and soil texture. The intermediate pool (SOC2) includes resistant plant material derived from structural plant tissue and soil-stabilized products derived from the active and surface microbial pools. It has a turnover rate (residence time) of around 5 to 20 yr depending on soil texture, soil disturbance, and environmental conditions. The passive pool (SOC3) is resistant to decomposition and includes physically and chemically stabilized SOC with a turnover time of 200 yr or longer depending on environmental conditions. These SOC fractions vary with time and are affected by soil texture and management, which in turn can determine the long-term trends of organic C.

Model-Based Procedure for Initializing Soil Organic Carbon Pools

We have developed an approach for estimating SOC pools in soil where crops have been grown under rotation systems or changing management for a short period of time relative to the turnover rate of the passive soil C pool (i.e., time periods of <500 yr). The procedure can be used to produce initialization values that approximate relative pool fractions, or it can be used directly to initialize pool fractions for a particular experimental field. The rationale for producing look-up tables is that some users may not be able to simulate the actual history for a field, and the tables provide useful approximations to those values using minimal information on land use history. In both cases, the procedure requires a measurement of initial total organic soil C ($CTOT_t$) at time $t = 0$ when the simulation is to start. The procedure does not attempt to estimate total SOC at time $t = 0$.

Creating Tables of Intermediate Soil Carbon Fractions

To produce tables of SOC fractions, we focused on the intermediate C pool (SOC2) in that the changes in SOC are mostly due to this pool when the simulation duration is <50 yr; during that time, changes to the C in the passive pool (SOC3) are relatively small. The SOC2 fraction is unknown at time $t = 0$, but if it can be estimated, then with the measurement of total SOC, the other SOC pool fractions (FC_i, for $i = 1–3$) can be estimated. If we have an estimate of soil C in the intermediate pool (SOC2), we can compute the fraction of soil C (%) in that pool ($FC_{2,0}$) as

$$FC_{2,0}=\frac{SOC2_0}{CTOT_0} \qquad [1]$$

Furthermore, because the active C pool fraction is small (typically on the order of 1 to 5% of total C), an approximation of the initial C fraction in this pool is

$$FC_{1,0}=0.02 \qquad [2]$$

where $FC_{1,0}$ is the fraction of C in the active pool at time $t = 0$. This fraction size is arbitrary; because the active pool is small and has a rapid turnover rate, it will quickly adjust and come into equilibrium within the first simulated year. Finally, the fraction of the passive pool at time $t = 0$ ($FC_{3,0}$) is approximated by

$$FC_{3,0}=1.00-0.02-FC_{2,0} \qquad [3]$$

These estimated $FC_{i,0}$ values (where i is the pool fraction and 0 is the time) are then used, along with the measured total soil organic C ($CTOT_0$), to initialize all of the C pools. The tables only need $FC_{2,0}$, and Eq. [1–3] are used to approximate the other pool fractions using the measured $CTOT_0$. If the cropping system and its management has been practiced consistently for an extended period of time (e.g., 100 yr or more), then it could be assumed that this intermediate soil C pool is near its steady-state value for the climate and soil at this site. Therefore, the previous cropping system could be simulated for 100 yr and the final value of simulated $SOC_{2,100}$ used in Eq. [2] along with the measured $CTOT_0$ to initialize the simulation. If the cropping system has been in place for only a few years, however, the intermediate pool would probably not be at its steady-state value. In this study, we estimated transient SOC2 values using preliminary simulation results based on soil texture, years during which the prior cropping system had been in place, and an estimate of field management prior to that crop.

For example, a field with a known measured SOC value may have been under maize (*Zea mays* L.) cropping for the past 8 yr, and before that the field was in fallow. To use the model to estimate the SOC fractions for this example, the cropping system grown during the last 8 yr needs to be simulated, using initial conditions estimated for the field when that cropping system was first started, with the objective of matching the current measured SOC value (after 8 yr). Although the initial values of the soil C fractions 8 yr ago may not be accurate, the effects of using incorrect estimates of the intermediate soil C pool fraction will diminish with time as SOC2 transitions toward a new steady state.

Direct Use of Procedure for a Simulation Study

Tables created using the above procedure can aid model users in selecting the most suitable SOC fraction distribution to properly initialize the model. If users do not have tables created for their climate and cropping systems, then they can use the procedure to initialize the SOC pools

Table 1. Physical and chemical characteristics of the soils used in the simulation scenarios.

Parameter	Concentration per layer							
	5 cm	15 cm	30 cm	45 cm	60 cm	90 cm	120 cm	150 cm
	%							
Sand								
SOC	0.29	0.29	0.28	0.24	0.24	0.18	0.11	0.05
Clay	3	3	3	3	3	3	3	3
Silt	5	5	5	5	5	5	5	5
Loamy sand								
SOC	0.7	0.7	0.66	0.58	0.58	0.43	0.26	0.12
Clay	6	6	6	6	6	6	6	6
Silt	12	12	12	12	12	12	12	12
Sandy loam								
SOC	0.7	0.7	0.66	0.58	0.58	0.43	0.26	0.12
Clay	10	10	10	10	10	10	10	10
Silt	32	32	32	32	32	32	32	32
Silt loam								
SOC	1.16	1.16	1.1	0.97	0.97	0.72	0.43	0.2
Clay	13	13	13	13	13	13	13	13
Silt	70	70	70	70	70	70	70	70
Silt								
SOC	1.16	1.16	1.1	0.97	0.97	0.72	0.43	0.2
Clay	5	5	5	5	5	5	5	5
Silt	85	85	85	85	85	85	85	85
Loam								
SOC	1.16	1.16	1.1	0.97	0.97	0.72	0.43	0.2
Clay	18	18	18	18	18	18	18	18
Silt	39	39	39	39	39	39	39	39
Sandy clay loam								
SOC	1.75	1.75	1.6	1.45	1.45	1.1	0.65	0.3
Clay	27	27	27	27	27	27	27	27
Silt	15	15	15	15	15	15	15	15
Silty clay loam								
SOC	1.75	1.75	1.6	1.45	1.45	1.1	0.65	0.3
Clay	34	34	34	34	34	34	34	34
Silt	56	56	56	56	56	56	56	56
Clay loam								
SOC	1.75	1.75	1.6	1.45	1.45	1.1	0.65	0.3
Clay	34	34	34	34	34	34	34	34
Silt	34	34	34	34	34	34	34	34
Sandy clay								
SOC	1.75	1.75	1.6	1.45	1.45	1.1	0.65	0.3
Clay	42	42	42	42	42	42	42	42
Silt	6	6	6	6	6	6	6	6
Silty clay								
SOC	1.75	1.75	1.6	1.45	1.45	1.1	0.65	0.3
Clay	47	47	47	47	47	47	47	47
Silt	47	47	47	47	47	47	47	47
Clay								
SOC	1.75	1.75	1.6	1.45	1.45	1.1	0.65	0.3
Clay	58	58	58	58	58	58	58	58
Silt	20	20	20	20	20	20	20	20

for any particular study. In this case, the model is initialized to simulate the cropping history in an iterative way to obtain the measured CTOT at the current time. To do this, SOC fractions from a table created for a similar climate and soil are used to initialize the soil for the beginning of the time period considered for the known cropping history (e.g., 20 yr ago). Because total SOC at the beginning of this period is unknown, a first guess approximation is made based on soil texture and climate. The model is then executed for the duration of the cropping history time period—20 yr in this example. The simulated final total SOC is compared with the current SOC value, and if these are equal, the final distribution of SOC fractions is used with the measured SOC to restart the simulation of the cropping system being studied. If the measured and simulated values are not equal, then the procedure is repeated by changing the initial CTOT. This is repeated iteratively until the measured value of SOC at the start of the experiment (i.e., the end of the antecedent simulation) is adequately predicted. At this point, the intermediate (SOC2) and stable organic C (SOC3) fractions can be noted and used to initialize the model.

Simulation Scenarios for Estimating Initial Soil Organic Carbon Pool Fractions

We defined five scenarios for estimating soil C pool fractions and created tables to demonstrate the approach: (i) previously cultivated soil under good management during the cropping history time period; (ii) previously cultivated soil under poor management during the cropping history period; (iii) a previous grassland soil under good management during the cropping history period; (iv) a previous grassland soil under poor management during the cropping history period; and (v) initially degraded soil under good management during the cropping history period. The simulation analysis was performed using the DSSAT-CENTURY version 4.02 model (Hoogenboom et al., 2004) on 12 soil texture classes (Table 1) to demonstrate the procedure and results for different combinations of soil texture. We simulated a maize crop planted on 4 April of each year. In the first scenario, we used a soil that had been cultivated before the known cropping history time period and imposed a nonlimiting fully irrigated crop management with high N supply (306 kg N ha^{-1}) (good management) to eliminate variations with time associated with N stress and rainfall variability. The management used for the second scenario had no N or irrigation applications (poor management). The third and fourth scenarios had a grassland soil cover before the time when the cropping history started, and crop management during the cropping history period used the same good or poor management as the first two scenarios. The initial SOC used in these scenarios was higher due to expected higher organic matter residues from roots and plant litter present in the soil. This set of simulations was performed with a one-time addition on the starting date of 4.0 Mg ha^{-1} of fresh organic matter residues to approximate the conditions encountered when a grassland is converted to a cultivated field. For the final scenario, a previously degraded soil with a low starting SOC2 fraction was used and good management was imposed to simulate the effect of this management combination on the dynamics of the SOC pool.

It is important to emphasize that in this study, we did not create universal tables of SOC fractions but illustrated a generic approach to SOC pool initialization based on climate, soil type, and management. For this reason, we selected one high-quality climate data set and various soil types and management strategies to investigate the sensitivity of the SOC pool dynamics. It was our intent to illustrate the procedure and how users can potentially adopt it to create site-specific SOC fractions based on the soil and climatic conditions of their locations. For the model simulations, 20 yr of observed daily weather data from Tifton, GA, were used as inputs. Monthly average air temperature (°C), precipitation (mm d^{-1}), and solar radiation (MJ m^{-2} d^{-1}) are summarized in Table 2, computed using the 20 yr of historical daily weather data for this site. The initial soil C fractions for these 100-yr simulations were set to the values for cultivated and grassland suggested by Gijsman et al. (2002).

These represent only a small fraction of cases that may be needed for practical use of this approach. If simulations are performed continuously for long periods of time, say 1000 or more yr, total SOC and pool fractions can be very different from those obtained using this approach, and this procedure would not be needed. The procedures described above are generally applicable, although the pool fractions obtained in this study are specific to the particular site and management practices and are not intended to be universal.

Table 2. Weather data for Tifton, GA, expressed as monthly averages.

Month	Temperature	Rain	Radiation
	°C	mm	MJ m^{-2} d^{-1}
January	9.2	4.2	4.2
February	11.5	3.7	3.7
March	14.9	4.5	4.5
April	18.2	2.2	2.2
May	22.7	2.0	2.0
June	25.6	3.6	3.6
July	27.0	3.8	3.8
August	26.6	3.2	3.2
September	24.2	3.4	3.4
October	19.4	2.5	2.5
November	14.9	2.6	2.6
December	10.4	2.7	2.7

Validation on Long-Term Crop Rotation Experiment

The study site selected to evaluate the proposed procedure was the W.K. Kellogg Biological Station (KBS) Long-Term Ecological Research (LTER) site (42°24′ N, 85°24′ W) in southwest Michigan (Grandy et al., 2006a). Tillage treatments were established in 1989 in six replicated, 1-ha plots in a randomized complete block design. The soils present on the LTER site are Kalamazoo (a fine loamy, mixed, semiactive, mesic Typic Hapludalf) and Oshtemo (a coarse-loamy, mixed, active, mesic Typic Hapludalf). The site was cleared of trees (roots were left in place to decompose) in 1956 and thereby converted from a northern hardwood forest to a mid-successional grassland community that has since been mowed each fall, with mown biomass left in place. The site was principally in continuous corn production for >20 yr before the establishment of the LTER project in 1989.

The crop rotation before 1995 consisted of maize followed by soybean [*Glycine max* (L.) Merr.]. In 1995, wheat (*Triticum aestivum* L.) was planted after soybean, initiating a maize–soybean–wheat rotation. Primary tillage consisted of spring moldboard plowing from 1989 to 1998 and spring chisel plowing from 1999 to 2002. Secondary tillage consisted of disking before planting. Fertilizer was broadcast on maize and wheat. Soybean did not receive N, P, or K fertilization (Grandy et al., 2006b). Detailed information about annual applications can be found on the KBS LTER website (lter.kbs.msu.edu/about/experimental_design.php; verified 17 Nov. 2010).

For this study, we used the treatment defined as T1 (conventional tillage, high external chemical input). We built a management sequence file on the basis of the T1 treatment and executed the model for 13 yr using DSSAT version 4.02. The sequence file included a maize–soybean–wheat rotation, conventional tillage, N fertilization, and crop residue incorporation.

RESULTS AND DISCUSSIONS

Tabular Results

The simulated results of the SOC2 fraction for the 0- to 20-cm soil layer with time for the five scenarios and the 12 soil types are reported in Tables 3 to 6. Table 3 shows the changes in the 0- to 20-cm depth of a field that had been cultivated, under good or poor management practices, before these simulations for 12 soil types at Tifton, GA. The results of the first two scenarios demonstrated the sensitivity of changes in the SOC2 fraction with time to management and soil type. The initial SOC2 fraction used to initialize the soils for simulating the first two scenarios were typical values for a cultivated soil (FC_1 = 0.01%, FC_2 = 0.54%, FC_3 = 0.44%) (A.J. Gijsman, personal communi-

Table 3. Changes in the intermediate soil organic C pool (SOC2) as a percentage of the total soil organic C with time in a cultivated soil (0–20 cm) under good and poor management practices for 12 soil types at Tifton, GA.

	SOC2 pool											
	0 yr		5 yr		10 yr		20 yr		60 yr		100 yr	
Soil	Poor	Good	Poor	Good	Poor	Good	Poor	Good	Poor	Good	Poor	Good
	%											
Sand	0.54	0.54	0.45	0.50	0.41	0.51	0.30	0.58	0.10	0.68	0.06	0.70
Loamy sand	0.54	0.54	0.43	0.44	0.40	0.39	0.37	0.37	0.13	0.39	0.05	0.39
Sandy loam	0.54	0.54	0.46	0.49	0.45	0.47	0.45	0.49	0.23	0.55	0.10	0.56
Sandy clay loam	0.54	0.54	0.43	0.42	0.37	0.34	0.32	0.27	0.18	0.24	0.14	0.24
Sandy clay	0.54	0.54	0.44	0.43	0.39	0.35	0.34	0.29	0.20	0.25	0.16	0.25
Loam	0.54	0.54	0.46	0.47	0.44	0.43	0.43	0.42	0.29	0.43	0.19	0.44
Clay loam	0.54	0.54	0.45	0.45	0.41	0.40	0.37	0.35	0.26	0.31	0.20	0.31
Clay	0.54	0.54	0.45	0.46	0.41	0.40	0.36	0.36	0.24	0.32	0.19	0.32
Silt loam	0.54	0.54	0.47	0.50	0.46	0.50	0.46	0.52	0.34	0.55	0.25	0.56
Silt	0.54	0.54	0.48	0.50	0.47	0.51	0.47	0.53	0.35	0.56	0.26	0.56
Silty clay loam	0.54	0.54	0.46	0.47	0.43	0.44	0.40	0.41	0.28	0.39	0.22	0.39
Silty clay	0.54	0.54	0.47	0.48	0.44	0.45	0.42	0.43	0.33	0.42	0.26	0.42

Table 4. Changes in the intermediate soil organic C pool (SOC2) as a percentage of total soil organic C with time in a grassland soil (0–20 cm) under good and poor management practices for 12 soil types at Tifton, GA.

Soil	SOC2 pool											
	0 yr		5 yr		10 yr		20 yr		60 yr		100 yr	
	Poor	Good	Poor	Good	Poor	Good	Poor	Good	Poor	Good	Poor	Good
	%											
Sand	0.64	0.64	0.53	0.56	0.48	0.56	0.37	0.60	0.12	0.68	0.06	0.70
Loamy sand	0.64	0.64	0.50	0.50	0.45	0.43	0.41	0.39	0.14	0.39	0.05	0.39
Sandy loam	0.64	0.64	0.53	0.55	0.51	0.51	0.49	0.51	0.24	0.55	0.10	0.56
Sandy clay loam	0.64	0.64	0.50	0.49	0.42	0.38	0.34	0.29	0.18	0.24	0.12	0.24
Sandy clay	0.64	0.64	0.51	0.49	0.43	0.40	0.36	0.30	0.20	0.25	0.14	0.25
Loam	0.64	0.64	0.53	0.53	0.49	0.47	0.46	0.44	0.29	0.43	0.17	0.43
Clay loam	0.64	0.64	0.52	0.52	0.46	0.44	0.40	0.37	0.26	0.31	0.19	0.31
Clay	0.64	0.64	0.52	0.52	0.46	0.45	0.39	0.38	0.24	0.32	0.17	0.32
Silt loam	0.64	0.64	0.54	0.57	0.52	0.54	0.50	0.54	0.34	0.55	0.23	0.56
Silt	0.64	0.64	0.55	0.57	0.52	0.55	0.50	0.55	0.35	0.56	0.24	0.56
Silty clay loam	0.64	0.64	0.53	0.54	0.48	0.48	0.43	0.43	0.29	0.39	0.21	0.39
Silty clay	0.64	0.64	0.54	0.54	0.50	0.50	0.45	0.46	0.33	0.42	0.25	0.42

cation, 2002). Even though the same initial SOC fractions were used for all soils, the effects of field history and management varied significantly with soil type and with poor and good management. The SOC2 fraction in the sandy soil increased under good management, from 0.54 to 0.70% after 100 yr of simulation, while the stable organic fraction, SOC3, decreased to a value of 29%. Poor management in this scenario showed a continuous decrease in the SOC2 fraction, as expected due to its lower biomass production and amount of fresh organic matter returned to the soil.

In the silty clay loam soil, the SOC2 fraction varied during 100 yr under good management, from 0.54 to 0.39%, but significantly decreased under poor management, reaching a final value of 0.22 after 100 yr. The clay soil showed a SOC2 fraction decrease from 0.54 to 0.32% under good management but the SOC3 fraction increased as a consequence of the slow mineralization and the stronger organic C protection. In the cultivated scenarios, poor management showed an exponential decay function for all the soils.

Table 5. Changes in the intermediate soil organic C pool (SOC2), as a percentage of total soil organic C, with time in an initially degraded soil under good management practices for 12 soil types at Tifton, GA.

Soil	SOC2 pool					
	0 yr	5 yr	10 yr	20 yr	60 yr	100 yr
	%					
Sandy	0.06	0.17	0.30	0.48	0.67	0.70
Loamy sand	0.05	0.10	0.17	0.27	0.37	0.39
Sandy loam	0.10	0.15	0.25	0.39	0.54	0.56
Sandy clay loam	0.14	0.11	0.15	0.20	0.23	0.24
Sandy clay	0.16	0.12	0.16	0.21	0.25	0.25
Loam	0.19	0.16	0.24	0.33	0.43	0.43
Clay loam	0.20	0.15	0.20	0.26	0.31	0.31
Clay	0.19	0.15	0.21	0.27	0.32	0.32
Silt loam	0.25	0.21	0.31	0.43	0.54	0.56
Silt	0.26	0.22	0.32	0.45	0.56	0.56
Silty clay loam	0.22	0.17	0.24	0.32	0.38	0.39
Silty clay	0.26	0.19	0.26	0.34	0.42	0.42

Table 4 shows the effects of poor and good management in a field that had been a grassland before the start of the simulation study. The initial SOC2 fraction used for this scenario was 0.64% for all soils. The SOC2 fractions at the end of the 100-yr period under poor management were similar to the cultivated scenarios, meaning that near-steady-state SOC2 fractions were reached in both cases. The good management treatment in the previous-grassland field showed the same range of variation as for the previously cultivated soils, demonstrating that soil texture and management have greater impacts on SOC3 after 20 yr or more than the initial SOC2 fractions.

The changes in the SOC2 fractions with time in an initially degraded soil with good management practices are shown in Table 5. In this scenario, the SOC2 fraction for 0- to 20-cm depth increased with time from a minimum value of 0.05 in the loamy sand at $t = 0$ to a maximum of 0.70% in the sand soil after 100 yr. Good management increased SOC2 fractions in all soils even though different initial values were used for each soil type.

Further illustrations of how changes in initial SOC fractions, soil texture, and history affect changes in soil C mass with time are shown in Fig. 1 to 6. Figure 1a shows the changes in soil organic C mass with time for the 0- to 20-cm soil layer in a 100-yr maize monoculture under poor management following grassland in a clay soil. The total SOC content changed with an exponential decline from the initial value of 1.6 to 0.87% after 100 yr. This change was mainly due to decomposition of the SOC2 fraction while the stable C (SOC3) remained constant. Figure 1b shows the SOC fraction changes for the same scenario. The SOC2 fraction changed from an initial value of 0.64% to a value of 0.32%. The SOC1 fraction changed very little, with an approximate value of 1%. The dynamic of CTOT and the SOC fractions for the silt soil for the scenario beginning with grassland under poor management is shown in Fig. 2. The silt soil showed a slower decline from its initial CTOT of 1.08 to 0.64%, and the SOC2 fraction increased to about 0.80 after 100 yr. The CTOT in the sand soil changed from 0.26 to 0.11% (Fig. 3a), and the SOC2 fraction changed from 0.64 to 0.06%.

Table 6. Iterative procedure to predict the measured soil C and intermediate soil organic C fraction (SOC2) as a percentage of the total soil organic C, for a cultivated silty clay loam soil under good management.

Target		Total organic C after 18 yr		ΔIOC†	IOC + ΔIOC	Error		SOC2 after 18 yr	SOC2
%	kg ha^{-1}	%	kg ha^{-1}	%	%	kg ha^{-1}	%	kg ha^{-1}	%
1.71	44,525	1.53	39,809	1	1.73	4716	10.59	18,902	0.42
1.71	44,525	1.69	43,990	16	1.99	535	1.20	19,984	0.45
1.71	44,525	1.70	44,258	17	2.00	267	0.60	20,056	0.45
1.71	44,525	1.71	44,516	18	2.02	9	0.02	20,123	0.45
1.71	44,525	1.72	44,785	19	2.04	−260	−0.58	20,195	0.45
1.71	44,525	1.73	45,041	20	2.06	−516	−1.16	20,262	0.46
1.71	44,525	1.74	45,310	21	2.07	−785	−1.76	20,332	0.46
1.71	44,525	1.75	45,568	22	2.09	−1043	−2.34	20,400	0.46
1.71	44,525	1.76	45,836	23	2.11	−1311	−2.95	20,471	0.46
1.71	44,525	1.77	46,094	24	2.12	−1569	−3.52	20,539	0.46

† ΔIOC, difference from initial organic C.

The effects of good management on the changes in the CTOT and SOC fractions in the maize rotation with the prior grassland field history are illustrated in Fig. 4 to 6. The CTOT changed from 1.60 to 1.25% after 100 yr, while the SOC2 fraction decreased from 0.64 to 0.32% and the SOC3 fraction increased from 0.34 to 0.67% (Fig. 4a–4b). The SOC2 fraction in the silty soil slightly decreased; consequently the stable pool increased from 0.34 to 0.43% (Fig. 5a–5b). Figure 6 shows the dynamics of the CTOT (Fig. 6a) and SOC fractions (Fig. 6b) in the sand soil. For this case, the CTOT increased from 0.25 to 0.30% and the stable C fraction decreased from 0.34 to 0.29%.

Direct Use of the Procedure

Table 6 illustrates the iterative procedure more clearly using an example from a silty clay loam soil where the total SOC (CTOT, %) and SOC fraction changes were simulated for 18 yr to reach a measured target value of 2.06% equivalent to a total amount of 44,525 kg ha^{-1}. The simulated total SOC varied after 18 yr based on the different initial organic C used iteratively in the procedure. The difference in organic C between the initial organic C and the organic C used in the simulation can be added to (Table 6, column ΔIOC) or subtracted from, as in the case of the sand (Table 7, column ΔIOC), the initial soil C to adequately predict the target organic C value. In our simulations, we changed CTOT by 0.01% increments until the simulated and measured

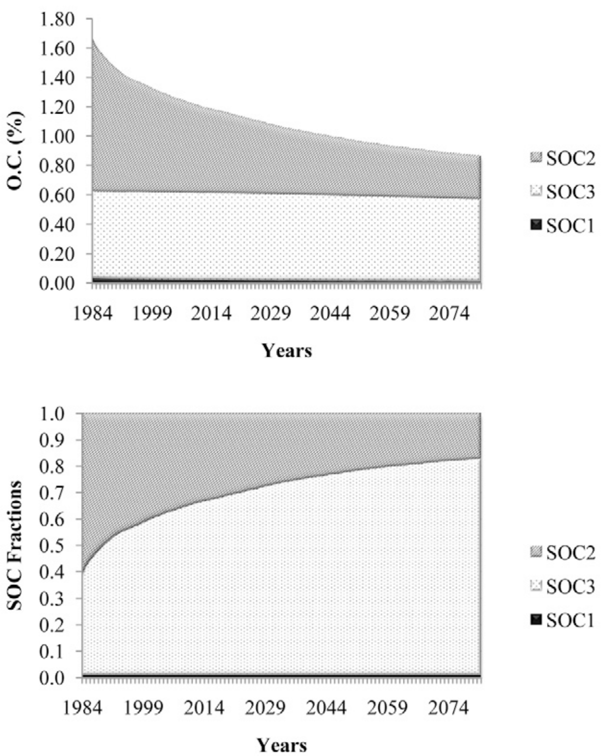

Fig. 1. Changes in (a) soil organic C (OC) and (b) the active soil organic C fraction (SOC1), the intermediate soil organic C fraction (SOC2), and the passive soil organic C fraction (SOC3) during 100 yr of a maize rotation following grassland in a clay soil (0–20 cm) under poor management.

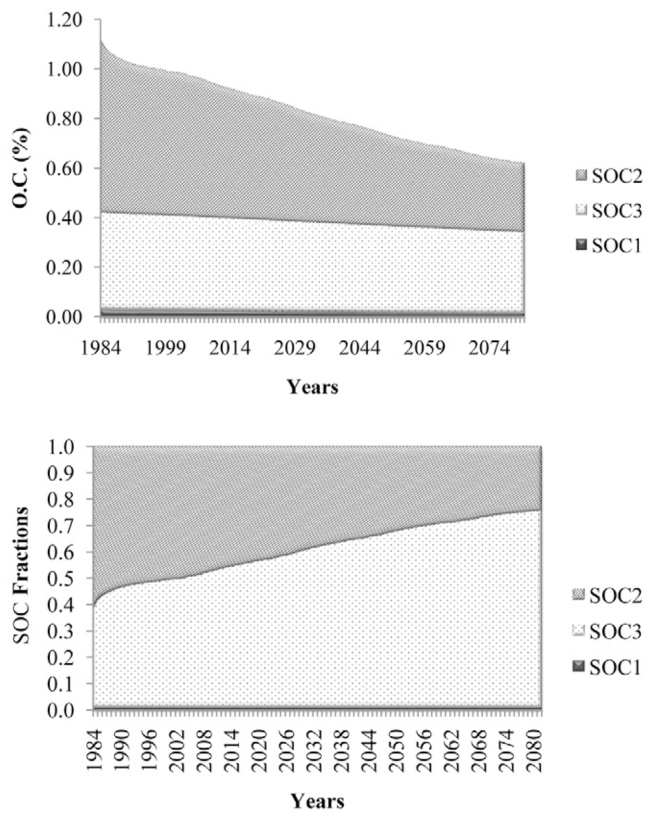

Fig. 2. Change in (a) soil organic C (OC) and (b) soil organic matter (SOM) fractions during 100 years of a maize rotation following grassland in a silt soil (0–20 cm) under poor management.

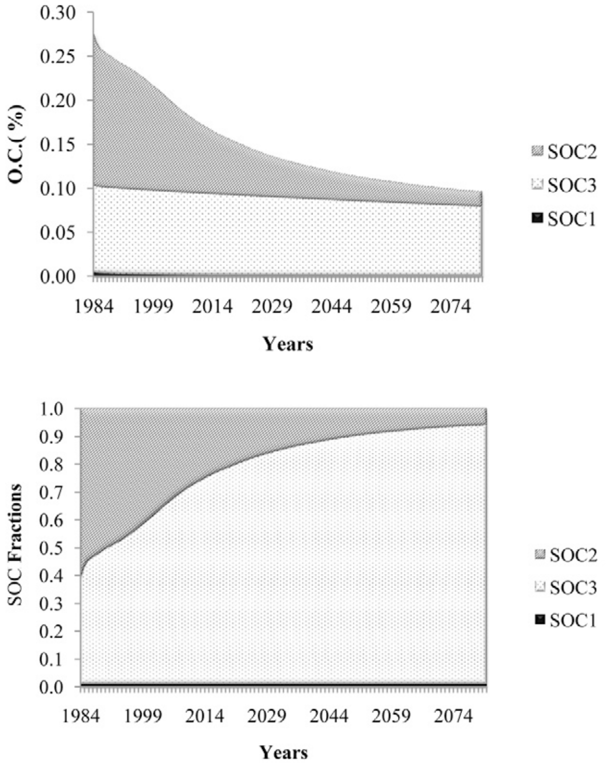

Fig. 3. Change in (a) soil organic C (OC) and (b) the active soil organic C fraction (SOC1), the intermediate soil organic C fraction (SOC2), and the passive soil organic C fraction (SOC3) during 100 years of a maize rotation following grassland in a sand soil (0–20 cm) under poor management.

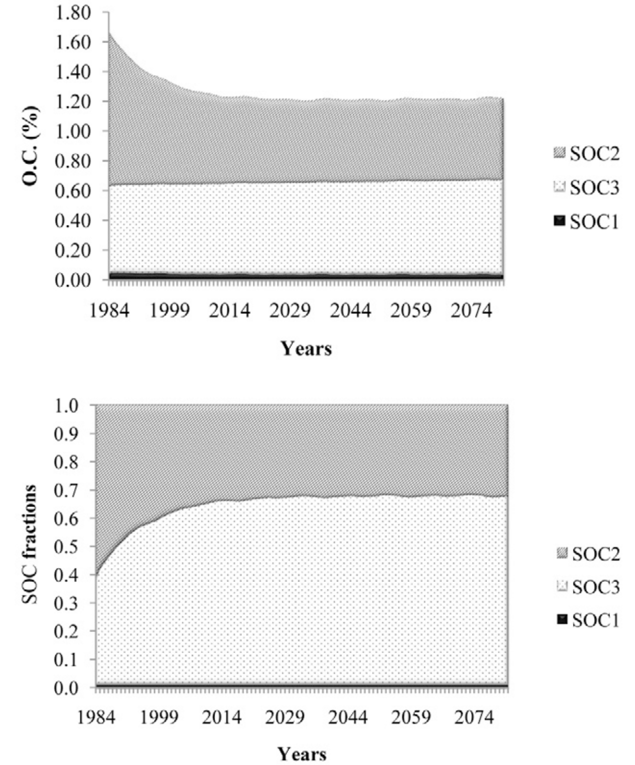

Fig. 4. Change in (a) soil organic C (OC) and (b) the active soil organic C fraction (SOC1), the intermediate soil organic C fraction (SOC2), and the passive soil organic C fraction (SOC3) during 100 years of a maize rotation following grassland in a clay soil (0–20 cm) under good management.

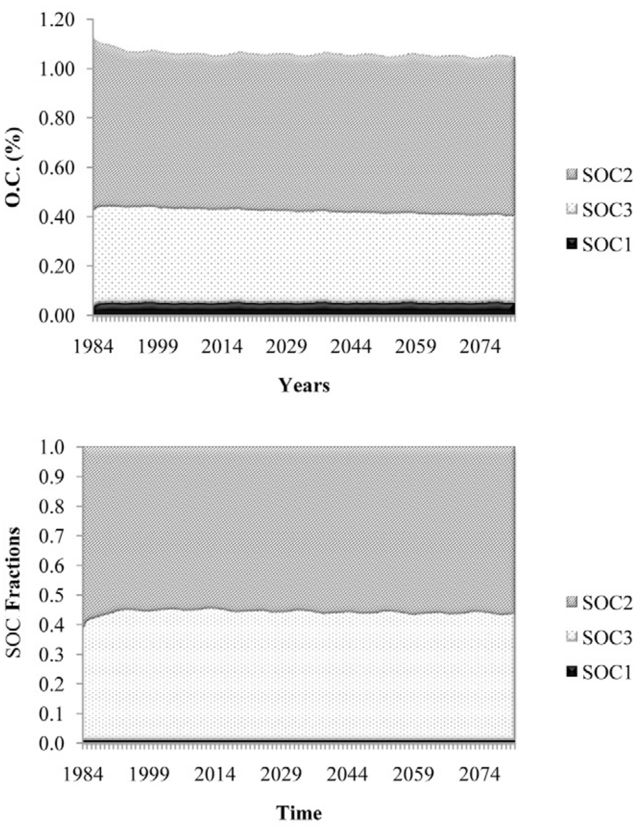

Fig. 5. Change in (a) soil organic C (OC) and (b) the active soil organic C fraction (SOC1), the intermediate soil organic C fraction (SOC2), and the passive soil organic C fraction (SOC3) during 100 years of a maize rotation following grassland in a silt soil (0–20 cm) under good management.

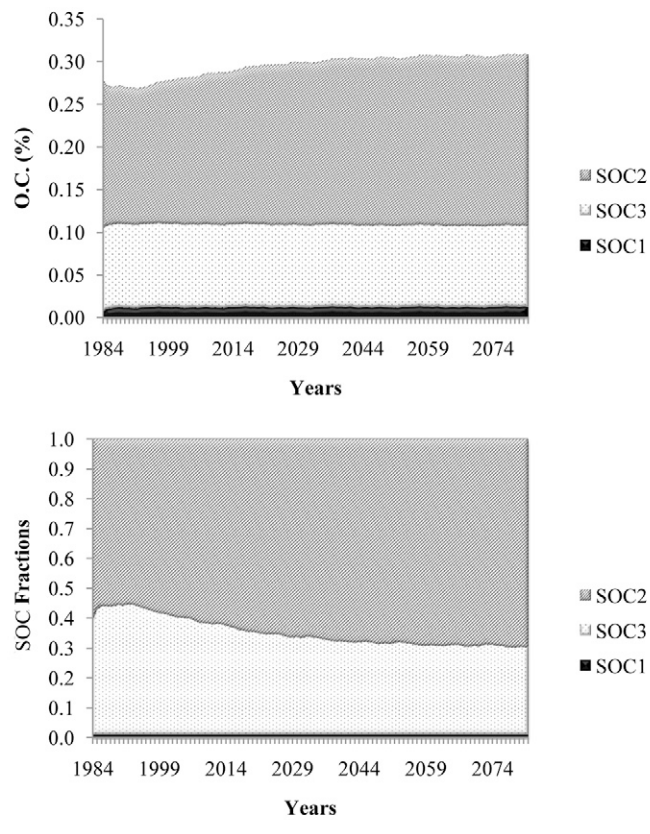

Fig. 6. Change in (a) soil organic C (OC) and (b) the active soil organic C fraction (SOC1), the intermediate soil organic C fraction (SOC2), and the passive soil organic C fraction (SOC3) during 100 years of a maize rotation following grassland in a sand soil (0–20 cm) under good management.

Table 7. Iterative procedure results for intermediate soil organic C fraction (SOC2) estimation for different soil types.

Texture	Initial organic C		Target		SOC2 fraction		ΔIOC†
	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%
Sand	0.27	8799	0.288	9546	0.559	5341	−8
Silt	1.12	30763	1.145	31373	0.535	16798	−2
Silt Clay Loam	2.02	52551	1.713	44525	0.452	20123	18
Clay	2.18	56567	1.713	44525	0.415	18475	27

† ΔIOC, difference from initial organic C.

target values were closest in magnitude. The smallest error between measured and simulated target CTOT values in this case was reached after changing our initial guess of CTOT by 0.18% after 18 iterations. The corresponding SOC2 fraction at the end of the 18 yr, to be used for further simulations, was 0.45%.

Table 7 shows the amount of SOC to be added to the initial estimate in this example to closely predict the target SOC value. Also shown are the SOC2 fractions to be used for future simulations. Note that to match the SOC under good management in a sand soil, the change in organic C was −0.08% in the sand soil and +0.27% in the clay soil.

Validation of Procedure Using a Long-Term Rotation Experiment

As mentioned above, Tables 4 to 6 developed for Tifton, GA, cannot be directly used for initializing SOC fractions in places with different climatic conditions. To evaluate the procedure presented here and to demonstrate estimation of SOC fractions in places other than Tifton, we used 13 yr of SOC values measured in the KBS study. We ran a maize rotation for 13 yr using an SOC2 value of 0.54%, which was found to be the best SOC2 fraction to minimize the error between the measured and simulated results after 13 yr (Table 8). The model performed well when compared with the measured values of SOC, with a RMSE of 0.023%. Using our procedure, compared with the Gijsman et al. (2002) partitioning, the improved initial values resulted in a reduction of 10% in the error between the model and measured values during the 18 yr.

Table 8. Measured and simulated organic C (0–20 cm) at Kellogg Biological Station using intermediate soil organic C fraction of the total soil organic C (SOC2) = 0.54%.

Year	Measured organic C	Simulated organic C	Error
	%		
1988	0.85	0.85	0
1989	0.84	0.84	0
1990	0.85	0.83	−0.2
1991	0.82	0.83	0.1
1992	0.81	0.83	0.2
1993	0.85	0.83	−0.2
1994	0.83	0.82	−0.1
1995	0.86	0.85	−0.1
1996	0.85	0.83	−0.2
1997	0.89	0.84	−0.5
1998	0.87	0.86	−0.1
1999	0.82	0.84	0.2
2000	0.81	0.85	0.4
2006	0.82	0.83	0.1

The CTOT percentage and SOC2 fractions for the KBS site (Fig. 7) show that the SOC2 at the end of the 13 yr changed from 0.54 to 0.52%. The latter value is the one to use for further simulations if the fate of soil C for this location were further investigated. The value of SOC2 for a cultivated loam soil under good management (like the conditions at the KBS site during 13 yr), for Tifton, GA, is around 0.47%. The values of SOC2 for Tifton and KBS are different, which demonstrates the interaction of climate with soils on SOC dynamics, in this case a faster overall turnover time in SOC in the warmer soils of Tifton. This suggests caution in using tables for climatically distinct locations, different from where they were created, unless they are only used to provide an indication of the magnitude of the SOC fraction to be used to initialize the iterative procedure proposed in this study.

CONCLUSIONS

We used an approach to demonstrate the effects and interactions of soil type and management on the variations in SOC pools. We used the DSSAT-CENTURY version 4.02 model and SOC equations to estimate the changes in SOC fractions under different

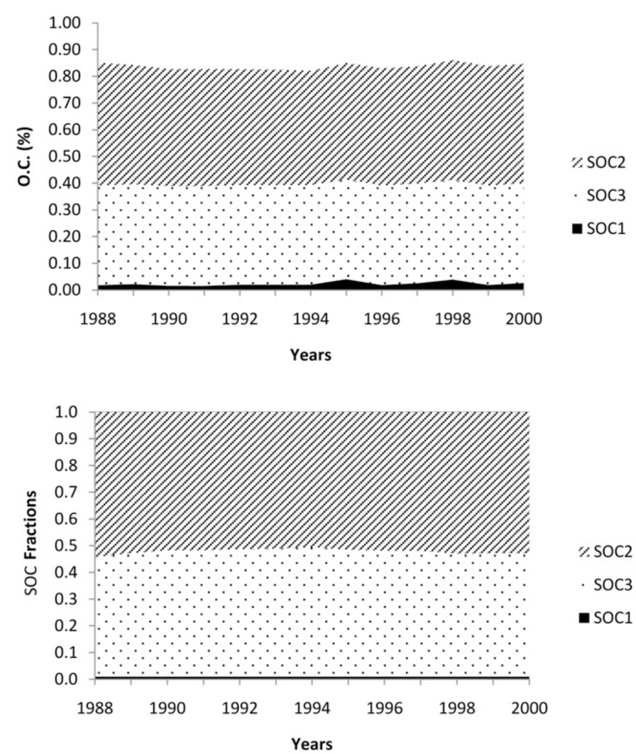

Fig. 7. Change in (a) soil organic C (OC) and (b) the active soil organic C fraction (SOC1), the intermediate soil organic C fraction (SOC2), and the passive soil organic C fraction (SOC3) during 100 years of a maize rotation following grassland in a loam soil (0–20 cm) under good management.

soil and management conditions with a high-quality climate data set recorded for Tifton, GA. We have shown how the approach can be used to simulate the cropping history in an iterative way to obtain the measured CTOT at the starting year for a field experiment in order to estimate the relative distribution of SOC across the model pools for subsequent modeling of the experimental period.

The advantages of using the proposed procedure are intuitive because it provides help for the user facing the difficult task of choosing the proper SOC fractions to initialize the dynamic model. This procedure should be adopted to create site-specific SOC fractions based on the soil and climatic conditions of a specific location. The model provided excellent results when compared with measured soil C data using the SOC fraction that minimized the error between measured and simulated results after the model was executed with the iterative procedure described in here.

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