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Simulation of management and soil interactions impacting SOC dynamics in sugarcane using the CENTURY Model

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Abstract

Newer methods of management and harvesting of sugarcane are being considered to improve soil and water conservation in Brazil. Our aim in this study was to evaluate soil C dynamics under sugarcane cultivation as influenced by the use of conservation management, using measurements from four different management systems and land use histories, i.e. conventional management with preharvest burning, no burning with residue retention and two systems without burning plus additional organic amendments. Field sites also differed in terms of soil texture. We compared field measurements of soil C stocks, ^{13}C and microbial biomass with simulated results from the Century ecosystem model for each of the sites and management histories. We also did long-term simulations of the management treatments and sites to approximate steady-state SOC levels, to explore potential management-induced differences in SOC stocks and interactions with soil texture. The model accurately represented treatment and site differences for total SOC stocks, in which SOC stocks were strongly affected by both rates of organic matter input to soil and soil clay content. However, the model tended to underestimate the relative contribution of sugarcane-derived C to total SOC for sites with high residue and external organic matter amendments. Measured microbial biomass C across the sites was closely aligned with relative amounts of organic matter input but did not appear to be strongly affected by soil texture, whereas the model predicted that both texture and organic matter input rate would impact microbial biomass C. Long-term simulations of the conservation management alternatives suggested that SOC stocks could be maintained at or above levels in the original native Cerradão vegetation, whereas conventional practices using residue burning would result in a reduction of SOC to ca. 60% of native levels. Our results support the use of the CENTURY model as an aid to assess the impacts of different soil management practices on SOC stocks under sugarcane in Brazil.

Keywords: CENTURY model, modeling, organic system, residue burning, soil organic matter, sugarcane

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Introduction

The demand for bioethanol production is rapidly increasing worldwide (Lal, 2009) to provide a substitute for fossil-derived liquid fuels and to mitigate greenhouse gas emissions (Bordonal *et al*., 2012; Thorburn *et al*., 2012). Thus, attention has been given to sugarcane ethanol production in Brazil, which is currently the largest producer (FAO, 2011). Production is projected to increase further, to a total of 10 million ha (UNICA, 2013), which will produce 58.8 billion of liters of bioethanol by 2019 (CONAB, 2011).

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With this expansion of sugarcane cultivations there are concerns about soil degradation (Garside, 1997; Haynes & Hamilton, 1999; Dominy *et al*., 2002; Graham *et al*., 2002). A potential consequence of soil degradation under sugarcane cropping is the loss of soil organic matter (SOM) (Wood, 1985; Haynes & Hamilton, 1999) under conventional management, which includes the burning of crop residues (Dominy *et al*., 2002; Robertson & Thorburn, 2007; Galdos *et al*., 2009, 2010). To avoid soil degradation, newer methods of sugarcane harvesting that could contribute to increased soil C stocks (Galdos *et al*., 2009, 2010; Thorburn *et al*., 2012) are being considered. The conversion from manual to mechanical harvesting (i.e. without the use of preburning) leaves 10–20 Mg ha^{-1} yr^{-1} of dry matter (Galdos

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et al., 2010; Fortes *et al.*, 2012) as a residue cover on the soil surface after harvest. While surface residues decompose rapidly, between 8–19% of the postharvest residues remain on the surface one year after harvest (Urquiaga *et al.*, 1991; Spain & Hodgen, 1994; Galdos *et al.*, 2010; Fortes *et al.*, 2012).

Studies have shown that retaining sugarcane residues instead of burning may increase soil organic C over time (Robertson & Thorburn, 2007; Galdos *et al.*, 2009; Canellas *et al.*, 2010; Thorburn *et al.*, 2012). Organic matter inputs in the form of byproducts of sugarcane processing, such as vinasse and filter cake, and organic residues additions from crops other than sugarcane, are other promising management practices to increase soil C stocks (Leite *et al.*, 2004; Fließbach *et al.*, 2007; Araújo *et al.*, 2008). These management strategies and the integrated use of chemical fertilizers have being proposed to maintain SOM, improve soil quality, crop production and profitability (Fließbach *et al.*, 2007; Araújo *et al.*, 2008; Kaur *et al.*, 2008).

By restoring soil C stocks, improved management practices can also contribute to removing CO_2 from the atmosphere. However, the rates of SOM stabilization and the potential of a given soil to store carbon are directly dependent on the climate (temperature and precipitation), soil type (texture and mineralogy) and vegetation cover. In this context, the use of models can supplement studies that seek to estimate the capacity of soils to accumulate C. Modeled trends of the effects of different management strategies on SOM changes for different soil types and/or climate regimes can be compared to observations from long-term experiments or chronosequence studies.

The CENTURY model (Parton *et al.*, 1988; Metherell *et al.*, 1993) has been widely used to assess long-term SOM and nutrients dynamics under different agroecosystems. The model has been used in temperate conditions to evaluate different crop residues management systems (Paustian *et al.*, 1992; Parton & Rasmussen, 1994; Smith *et al.*, 1997; Del Grosso *et al.*, 2001). However, model simulations in tropical and subtropical conditions also have shown good results (Cerri *et al.*, 2004; Leite *et al.*, 2004; Galdos *et al.*, 2009, 2010; Tornquist *et al.*, 2009; Bortolon *et al.*, 2011), demonstrating its broad applicability.

Our aim in this study was to evaluate soil C dynamics under sugarcane cultivation as influenced by crop management, soil texture and organic matter additions using the CENTURY model. In addition, we evaluated the steady-state of soil C under sugarcane systems in Brazil managed with and without preharvest burning and with exogenous organic matter addition as organic fertilizer.

Materials and methods

Description of the study area

The study site is located in Goianésia, Goiás state (15°19′ S; 49°08′ W; elevation 649 m.), in the extreme north of the south-central region in Brazil (Fig. 1). The climate is classified as tropical savanna, hot and humid with dry winter and rainy summer (Aw), according to the Köppen classification. Average annual precipitation and temperature are 1602 mm and 24.3 °C, respectively. The soils are classified as Oxisols (Typic Hapludox).

The study area is within one of the most important sugarcane expansion areas in Brazil (with around 8.1% of current Brazilian production, corresponding to 8 47 000 ha) (UNICA, 2013) and is noted for the use of organic fertilizers, such as poultry manure composted with sugarcane residues, vinasse and filter cake from the sugar and bioethanol production chain.

This study evaluated soil C dynamics under four different sugarcane management systems, described in a Table 1. In addition, an area of the native forest - *forest*, was used as a reference. The native forest is classified as Cerradão and the main species are: *Qualea parviflora*, *Qualea grandiflora*, *Sclerolobium paniculatum*, *Byrsonima coccolobifolia*, *B. pachyphylla* and *Hymenaea stigonocarpa*.

The experimental design was a randomized design with different treatments (management systems) located on fields within the property serving a single sugar mill, within approximately 5 km of each other. All soils evaluated were classified as Oxisol (Typic Hapludox). Soil textures varied from clay (no burn and organic-12 practices) to heavy clay (burned and organic-4 practices and native vegetation). Soil properties by management practice in study areas are described in Table 1.

Soil physical, chemical, and biological analyses

Bulk density, pH, and clay, silt and sand content were determined according to EMBRAPA (1997) and Anderson & Ingram (1989). Prior to pH and texture analyses, soil samples were air-dried and sieved (2 mm) to remove stone fragments and coarse roots.

The pH was determined in water (1 : 2.5 soil : solution). The bulk density was determined with volumetric steel rings of 0.785 L internal volume.

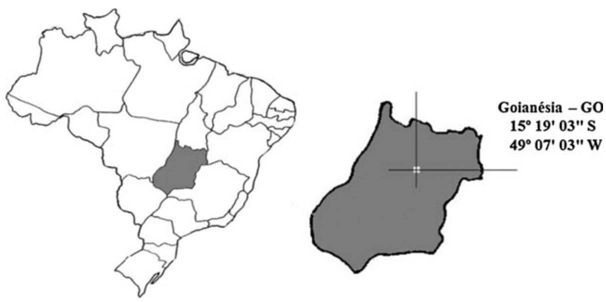

Fig. 1 Location of the study area in Goianésia, Goiás state, Brazil.

Table 1 Soil properties under sugarcane and native forest from Goianésia, Goiás state, Brazil, from 0 to 20 cm of depth

	Texture(g kg^{-1})				
Study area	Clay	Silt	Sand	Bulk density(g cm^{-3})	pH in $CaCl_2$
Burn	617 ± 34.87	139 ± 35.33	242 ± 4.93	1.15 ± 0.10	4.85 ± 0.20
No burn	442 ± 15.51	84 ± 9.90	472 ± 12.71	1.35 ± 0.08	4.82 ± 0.38
Organic-4	614 ± 18.53	154 ± 15.65	230 ± 7.81	1.15 ± 0.07	5.03 ± 0.23
Organic-12	351 ± 0.0	292 ± 7.94	357 ± 7.94	1.15 ± 0.12	5.23 ± 0.20
Native forest	597 ± 36.43	95.6 ± 34.56	305 ± 10.02	1.00 ± 0.11	4.31 ± 0.36

The total soil C and N were determined by dry combustion (Nelson & Sommers, 1996), through a CN elemental analyzer (TruSpec CN LECO 3000, St. Joseph, MI, USA). To calculate soil C stocks, we multiplied the content of soil C (g kg^{-1}), bulk density (g cm^{-3}) and depth of soil layer (cm).

The microbial biomass C (C-MB) was determined for the first 10 cm depth, using the chloroform-fumigation-extraction method (Vance *et al.*, 1987; Feigl *et al.*, 1995). The extraction was done on five replicates of 20 g soil subsamples that were extracted with 80 ml of a 0.5 M K_2SO_4 solution. C-MB in the extracts was determined by wet oxidation method (Walkley & Black, 1934). Microbial biomass C was obtained from the difference between soil organic C in fumigated and nonfumigated samples and adjusted by the correction factor for the extraction efficiency of 0.38 (Sparling, 1992).

The natural abundance of isotopic ^{13}C and ^{15}N (in ‰) relationships were determined by a CN elemental analyzer coupled to a mass spectrometer (Finnigan Delta-E, Science House Church Farm, Business Park, Corston Bath BA, UK). The natural isotopic abundance was calculated with the international standard Pee Dee Belemnite (PDB) as described in Bernoux *et al.* (1998). Furthermore, results of the natural abundance of $\delta^{13}C$ from soils were used to estimate the proportion of C derived from C4-cycle plants compared to the C3 pathway (Vitorello *et al.*, 1989).

The CENTURY model

We used the CENTURY model version 4.0 to simulate changes in soil C stocks, C-MB, $\delta^{13}C$ from soils and its corresponding C proportion from C4-plants pathway in areas cultivated with sugarcane under different management practices.

Three soil organic matter pools (active, slow, passive) are included in Century, each representing soil organic matter fractions with different potential decomposition rates. These pools are directly affected by edaphoclimatic factors (e.g., temperature, moisture, and soil texture), chemical composition of the litter (lignin/N, C/N), and tillage practices that control the decomposition rates and determine the flow of C and N among SOM pools (Metherell *et al.*, 1993).

In addition, the CENTURY model simulates above and belowground litter pools and the surface microbial pool related to surface litter decomposition. Above and belowground plant residues are partitioned into structural and metabolic pools as a function of the lignin to N ratio in the residue (increases in the ratio result in more residues being partitioned to the structural pools, which have slower decay rates).

For this study, the parameterizations related to organic matter in the CENTURY model are set to simulate the upper 20 cm of depth. Simulation output variables evaluated were soil C stocks (*somsc*), active pool SOC [*som1*(*c2*)], which represents soil microbial biomass and microbial products, and natural isotopic abundance of ^{13}C (*dsomsc*) (Metherell *et al.*, 1993).

Initializing CENTURY model

The CENTURY model requires input of climate, soil texture and N inputs (Parton *et al.*, 1993). In this study, we used climate data (monthly maximum and minimum average temperature and precipitation) for the period 1961–2011. The data sources were Instituto Nacional de Meteorologia (INMET) - Banco de Dados Meteorológicos para Ensino e Pesquisa (BDMAP), and Empresa Brasileira de Pesquisa Agropecuária - Unidade Arroz e Feijão (EMBRAPA Arroz e Feijão). Weather data for interior areas of Brazil are scarce and therefore we needed to combine data from several stations, including Goiânia (176 km distant from sampling areas, for 1961–1979); from Pirenópolis (105 km distant, for 1980–1982); from Santo Antonio de Goiás (153 km distant, for 1983–2000); and from the study area (Jalles Machado, in Goianésia-GO) for 2000–2011.

Goianésia has a mean annual precipitation of 160.2 cm, with mean a temperature maximum of 32.5 °C and mean minimum of 14.15 °C (Table S1).

Input data on soil texture, bulk density, and pH used are presented in Table 1.

The land use history for the study area and details about previous management practices were used to initialize model SOM pools through a spin-up procedure. First, precultivation conditions were represented by running the model to equilibrium (3000 years) for native Cerradão forest vegetation until 1950–1960 when forest vegetation was cleared with initial conversion into pasture. Management practices for pasture and crop cultivation on each field prior to conversion into sugarcane were not precisely known so we assumed typical management practices for the region (Fig. 2, Table 2). The model was then run for the different sugarcane management systems based on recorded management histories.

The periods between conversions of native forest into sugarcane were 34, 36, 36, and 27 years for burn, no burn, organic-4, and organic-12 sites, respectively. The simulations for sugarcane sites were done using parameterization for the sugarcane crop developed by Galdos *et al.* (2009, 2010) (Table S1, S2, S3, S4).

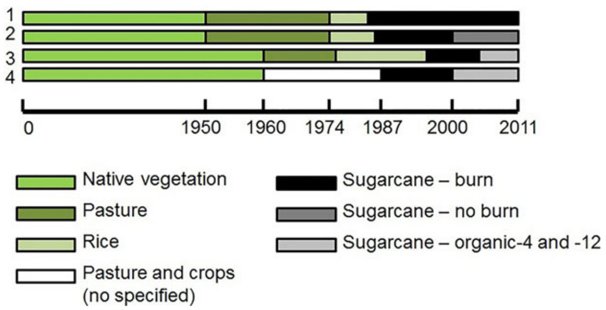

Fig. 2 Site sequence of land use and management. 1: burn site, 2: no burn site, 3: organic-4 site, and 4: organic-12 site.

Table 2 Description of period of time for sugarcane areas, and timeline before implantation

Characteristics	Burn	No burn	Organic-4	Organic-12
Period with sugarcane crop (years)	27	24	15	24
Period of under each management system (years)				
Burn	27	13	11	12
No burn	–	11	–	–
Organic	–		4	12
Period before sugarcane introduced				
Year of deforestation	1950	1949	1959	1959
Pasture (years)	24	24	16	–
Rice and other crops (years)	8	10	18	–
Pasture and crops no determined	–	–	–	26

Burn site. The sugarcane crop was traditionally harvested after burning the tops and dry leaves, mainly to facilitate manual cutting operations. Some areas still maintain this management, although there are currently laws for some states in Brazil to limit burning. The burned site was simulated using preharvest burning, for 27 years, and common mineral fertilization practices. We used input parameters for burning events developed by Galdos *et al.* (2009), in which 85% of the dry matter of the trash (leaves and tops) is removed by the fire, and 80% of the N in the residue material is lost to the atmosphere.

No burn site. Systems with unburned or 'green cane', from which trash is retained as an undisturbed layer on the soil surface are more environmentally favorable than the traditional burned system because of reduced runoff and soil erosion, reduced air pollution, and the potential increase soil in C accumulation (Leal *et al.*, 2013). In this study, we simulated the no burn site with the initial 13 years of sugarcane with burning and, the last 11 years with no burn preharvest.

Organic matter addition sites. The integrated use of chemical and organic fertilizers is being advocated to maintain SOM and crop production (Bulluck *et al.*, 2002; Kaur *et al.*, 2008). Of particular interest is the use of the residues generated in the sugar and bioethanol production chain as organic amendments to stabilize soil C. We simulated filter cake and vinasse organic amendment inputs which are byproducts generated in large quantities and have favorable physiochemical characteristics (such as high organic content). Filter cake, a high fiber content residue, is generated in the processing of sugarcane into sugar and bioethanol. The composition of the filter cake used in this study was based on analysis available in the literature: 228 g C kg^{-1}, 12 g N kg^{-1}, and 160 g lignin kg^{-1} (Orlando Filho *et al.*, 1991; Galdos *et al.*, 2009). Vinasse is a liquid residue high in nutrients, mainly in potassium, which is produced in the distillation step of the ethanol production. The composition used in the modeling was based on the analysis reported by Demattê *et al.* (2004), with 11.56 g C L^{-1} and 0.42 g N L^{-1}.

Modeling soil $\delta^{13}C$ and the proportion of C derived from C4 plants

Because the sugarcane (C4 plants) fields were converted from native forest (C3 species, the $\delta^{13}C$ isotopic signatures can be used to distinguish between SOM fractions derived from Cerradão and SOM derived from sugarcane (Cadisch *et al.*, 1996), since C3 plants (forest) discriminate more strongly against the naturally occurring isotope than the C4 plants (sugarcane).

Based on the $\delta^{13}C$ ratio in soil, the amount of the total C (C_t) derived from forest (C_f) and from sugarcane (C_s) (Vitorello *et al.*, 1989) were calculated according to Eqn 1 (Cerri *et al.*, 2004):

$$C_s = C_t \cdot (\delta_c - \delta_f)/(\delta_s - \delta_f), \quad C_f = C_t - C_s \tag{1a}$$

$$PC_s = 100 \cdot (\delta_c - \delta_f)/(\delta_s - \delta_f), \quad PC_f = 100 - C_s \tag{1b}$$

where C_t is the total C content of the sugarcane soil layer, δ_c is the $\delta^{13}C$ value of the respective soil sugarcane layer, δ_f is the $\delta^{13}C$ value of the corresponding forest soil layer and δ_s is the $\delta^{13}C$ average value for sugarcane (−15‰). PC_s and PC_f is the percent of total C from sugarcane and forest, respectively.

The CENTURY model is able to partition C production by plants and C inputs from exogenous additions, into ^{12}C and ^{13}C isotopes for each C pool represented in the model. Input values are selected to define the $\delta^{13}C$ value for each vegetation type simulated, reflecting isotopic discrimination of C3 and C4 photosynthetic pathways. In Century, the coefficient for isotope discrimination was calibrated to give a slight increase in the $\delta^{13}C$ value for the residues relative to the live vegetation (Metherell *et al.*, 1993). We used measured soil $\delta^{13}C$ to compare with simulated values (*dsomsc*). As input to CENTURY model, we used the $\delta^{13}C$ for litter material of the forest (−28 ‰) and sugarcane residue (−15‰).

Simulating long-term steady-state responses

To simulate the long-term impacts of the different management practices, each of the sites were run to the year 2150, by which time SOC contents were approaching an equilibrium state. The intent was not to model future scenarios of sugarcane production *per se*, but rather to run the model for sufficient duration that most of the management-induced changes of SOC would be manifested. Thus mean climate conditions and static management were used for the long-term projections (i.e. projected climate changes, CO_2 increases, changes in sugarcane production potential, etc., were not considered). Further, to simplify the analyses and capture the differences in C accumulation capacity due to management alone, we ran each of the four management options for the same soils, using soil parameters from the lowest (35%) and highest (65%) clay content soils among the sites.

Statistical analysis

Statistical analyses of modeling results were done in accordance with tests proposed by Smith *et al.* (1997) to assess goodness-of-fit of the CENTURY model to the measured SOC stocks, C-MB and changes in δ^{13}C as a function of management practices and time since land use conversion. These metrics included root mean square error (RMSE), correlation coefficient (r), coefficient of determination (CD), mean difference (M), and coefficient of residual mass (CRM).

Results

Modeling soil C stocks

Differences in total SOC stocks showed the influence of both management and land use history and the effects of soil texture differences across sites (Fig. 3). As expected, SOC stocks were highest in the native forest. Of the sugarcane sites, the organic-4 site had high clay content (614 g kg^{-1}) that, combined with the organic inputs, resulted in the highest soil C stocks, both measured and simulated. On the other hand, the management with residue burning, despite having similar clay content (617 g kg^{-1}) to the organic-4 site, had a lower soil C stock, which reinforces the potential of conventional management practices (e.g., long periods of residue burning) to decrease soil C. While differences between the burned and unburned treatments were not significant, it's likely that the difference would have been greater if not for the higher clay content in the burn site, which compensated for lower residue inputs (Fig. 3). The interaction of soil texture with management was also evident when comparing the organic-4 with organic-12 sites, which have contrasting textures (Table 3). Although the organic-12 site had external organic amendments over a longer time (12 vs. 4 years), because of it higher sand and lower clay content, SOC stocks were lower than the site receiving organic amendments for only 4 years (organic-4 site) (Fig. 3).

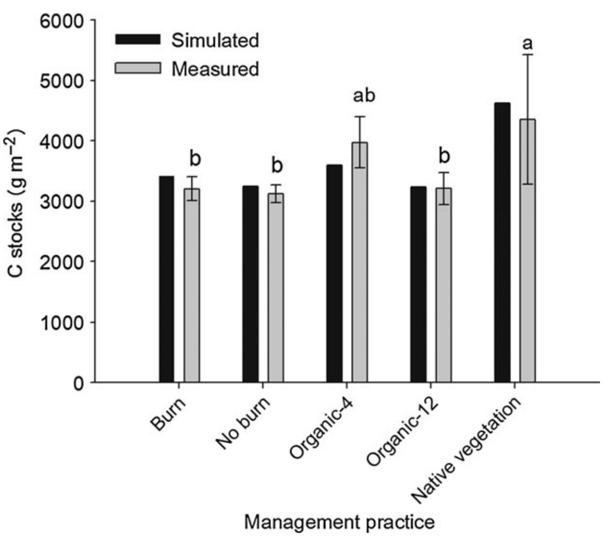

Fig. 3 Simulated and measured values of the C soil stocks in the 0–20 cm layer of the sugarcane sites with different tillage. Means followed by the same letter do not differ by Tukey test at 5%.

Model performance was good in replicating measured C stocks (Table 3), with r and CD values close to one, which indicates that much of the total variance of the observed data wereexplained by the model. In addition, the CRM value was close to zero, indicating a lack of bias in the distribution of predicted values with respect to measured values. The RMSE value showed a moderate difference between measured and simulated values, since this parameter indicates the percentage of the total difference between measured and simulated result.

Modeling soil C-MB

To make the comparison between simulated and measured values for microbial biomass C it was necessary to convert the CENTURY model values for 0–20 cm to values for 0–10 cm, the depth for measured microbial biomass data. This was done using a relationship derived from Cerri *et al.* (2004), by multiplying the simulated results by 0.56, the percentage (56%) of the total soil C

Table 3 Statistical tests applied for agreement between simulated and observed values of the sugarcane sites with different tillage

Statistical tests	C stocks (g m^{-2})	MB (g m^{-2})	δ^{13}C(‰) or % of C
r	0.90	0.63	0.95
RMSE	6.59	36.29	−17.02*
CD	0.92	9.39	0.77
M (g m^{-2})	−50.99	−2.33	3.06
CRM	−0.014	−0.5	−0.16

C stocks: soil C stocks, MB: C soil from microbial biomass, δ^{13}C: abundance natural isotopic $^{13/12}$C from soil, r: correlation coefficient, RMSE: root mean square error of model, RMSE$_{95\%}$: 95% confidence limit, CD: coefficient of determination, M: mean difference, CRM: coefficient of residual mass
*^{13}C results are expressed in negative values.

present in the 0–10 cm layer in relation to the total soil C contained in the 0–20 cm layer reported in that study.

The CENTURY model simulation results agreed with the measured results (Table 3) of the C-MB for the forest site, the organic-12 site and the no burn site. The model estimates where high compared to measured values at the organic-4 and the burn site.

The measured data showed a clear trend of increasing microbial biomass C with increased organic matter additions and improved management (Fig. 4). Interestingly, the trend in C-MB does not appear to show the same types of interactions with soil texture as was seen for total SOC. For simulated microbial biomass, represented by the active C pool, the observed trend with increasing organic matter additions was much weaker, with smaller differences among treatments. The biggest discrepancy between the measured and modeled microbial biomass was for the burned site, where the model predicted higher C-MB in the burned vs. the unburned site. Since soil texture also influences active C pool dynamics in the model, the model suggests (as for total SOC) that the texture effect compensates for the lower C inputs, but that prediction was not supported by the data.

Modeling soil δ^{13}C and the proportion of C derived from C4 plants

Observed trends for δ^{13}C clearly showed the effect of increasing sugarcane-derived residue along the management sequence (burn<no burn<organic-4<organic-12), with δ^{13}C values ranging from −20 to −15‰, compared to the δ^{13}C (−26‰) of the native C3 forest vegetation (Fig. 5). Although the CENTURY model tended to overestimate δ^{13}C values, the modeled trend generally followed the observed, except for the organic-4 system (r = 0.95, Table 3).

The model underestimated the proportion of total SOC from derived from C4 plants (Fig. 6) for all sites, particularly for the sites receiving organic amendments. While measured δ^{13}C for the organic-12 site indicated that 75% of the forest-derived C had been replaced by sugarcane-derived C, the model predicted around 54%. Some of the differences between measured and modeled values may lie in the uncertainties in the timeline of land use change and earlier management practices. However, the fact that the model predicted total SOC contents well, suggests that the model tended to underestimate the amount of sugarcane-derived C stabilized as SOM while overestimating the stability/retention of the original forest-derived SOC.

Simulation of long-term impacts

Simulations for each of the sites and management treatments were extended for an additional 140 years (to 2150, assuming no change in climate) to view the full impacts of site and management differences as SOC stocks approached steady-state conditions. Differences in preconversion (1950) SOC stocks reflect the differences in soil texture and ranged from ~3700 to 4900 g m^{-2}, with the highest levels in the higher clay sites.

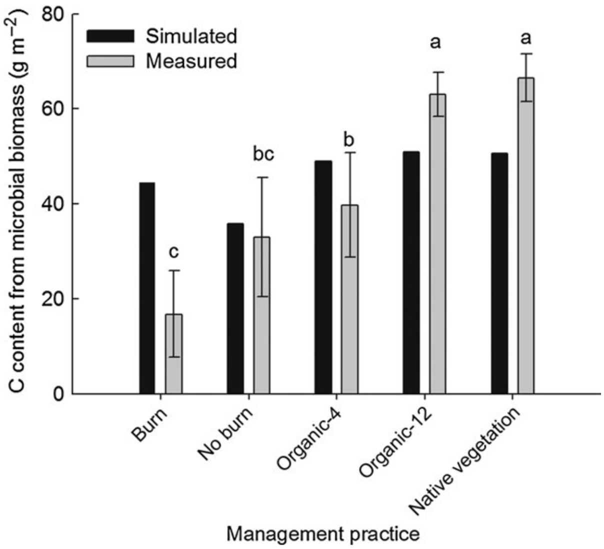

Fig. 4 Simulated and measured values of the C soil from microbial biomass in the 0–10 cm layer of the sugarcane sites with different tillage. Means followed by the same letter do not differ by Tukey test at 5%.

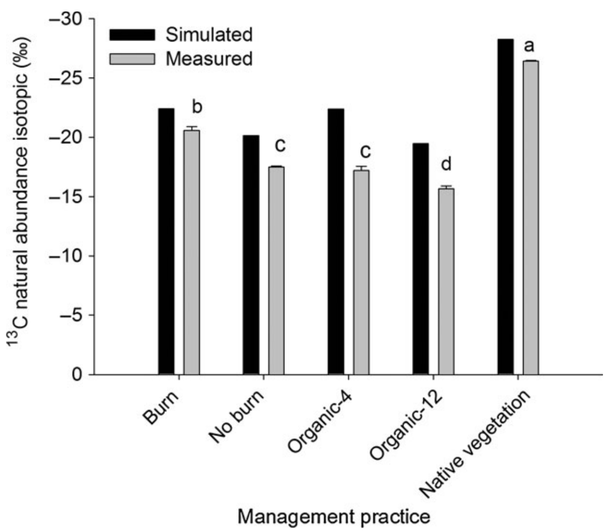

Fig. 5 Simulated and measured values of the δ13C soil in the 0–20 cm layer of the sugarcane sites with different tillage. Means followed by the same letter do not differ by Tukey test at 5%.

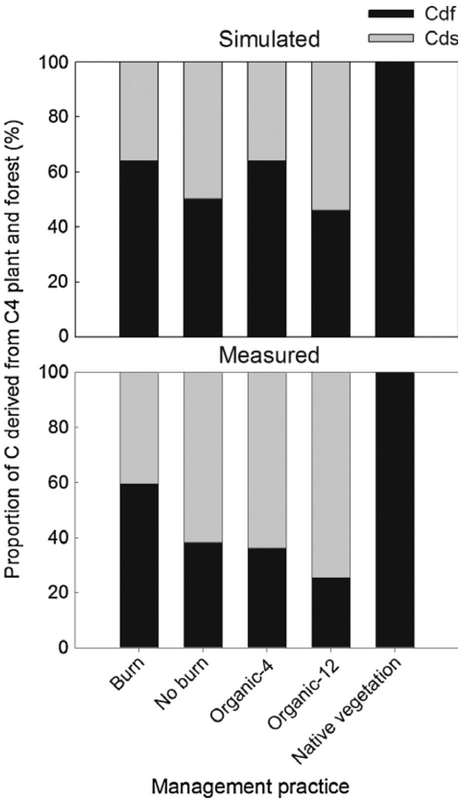

Fig. 6 Simulated and measured values of the proportion of C derived from forest (C3) and sugarcane (C4) in the 0–20 cm soil layer for sugarcane sites with different tillage systems and native forest (equilibrium). (Cdf: percentage of C derived from forest; Cds: percentage of C derived from sugarcane).

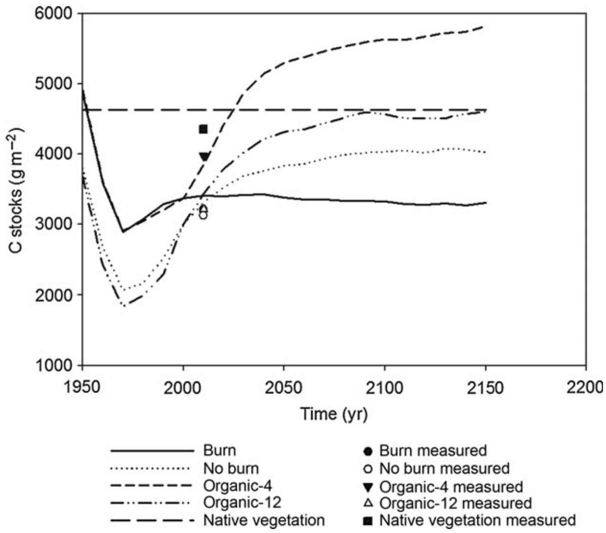

Fig. 7 Simulation of the soil C stocks (somsc), in the 0–20 cm soil layer (Fig. 1) until 2150 years, including the measured punctual (2011 measured).

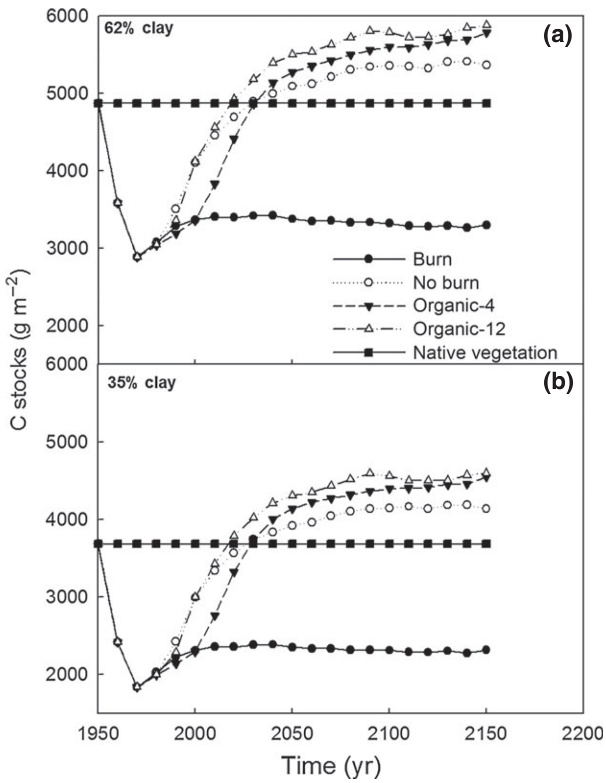

Fig. 8 Simulation until 2150 year of the soil C stocks (somsc) in the 0–20 cm soil layer for the highest clay (a) and highest sand (b) soils used in this study (Fig. 1).

The use of burn management resulted in a relative fast establishment of the lowest steady-state of soil C, which practically remained unchanged for the simulation period (Fig. 7). Relative to conventional management (burning), the model predicted substantially higher SOC with the adoption of conservation management practices, independent of soil texture. Retaining residues (no burn), ultimately resulted in a SOC stock increase in ca. 800 g m^{-2} relative to the burn treatment. Additional organic amendments were predicted to yield the highest SOC stocks. The site with a high clay soil was projected to reach the highest SOC level, exceeding levels under native forest, highlighting the capacity for high clay soils to accumulate soil C.

To assess the interactions of management with soil texture, we simulated each of the management system for the two soils having the lowest and highest clay contents. The trends in soil C over time were the same for the higher and lower clay soils for the various managements. In both soils, improved management (no burn, soil amendment) led to large increases in C stocks above unimproved management (burn) (Fig. 8).

The differences in soil C stocks between the sites with 62% and 35% of clay were 990, 1230, 1240, and 1280 g m^{-2}, respectively for burn, no burn, organic-4, and organic-12 sites.

Discussion

Total soil C dynamics

Both measured and modeled soil C stocks were highest under native forest compared to all sugarcane sites. This is consistent with many studies (e.g., Marchiori & Melo, 2000; Dominy *et al.*, 2002; Galdos *et al.*, 2009; Kaschuk *et al.*, 2011; Souza *et al.*, 2012) showing that land use change from native conditions, in general, is followed by a significant reduction in the quantity of OM; more than 50% of the accumulated SOM in tropical soils can be lost in the first years of cultivation (Mielniczuk, 1999). Most of the loss of original soil organic C is the result of agricultural management practices that reduce crop plant residue inputs, increase mineralization rates, and intensify tillage disturbance, decreasing the amount of physical protection for SOC (Six *et al.*, 2002).

However, areas that have been converted to agriculture use can recover much of the SOC lost through good management practices. The management regime without residue burning and with organic amendments, as the organic-4, which had a clay content very similar to the native forest site, seems to have accumulated a significant amount of SOC over a short period of time. This result highlights the need for more knowledge about the influence of the soil management practice, emphasizing which management practices best contribute to increasing soil C stock. However, management interacts with other factors, such as the soil texture, mineralogy and climatic conditions, and these must also be considered in addition to those related to agricultural practices.

In our study, the results for the sugarcane sites emphasized the importance of soil texture as well as management practices in the soil C accumulation, as evidenced by the lower C stocks in the no burn (lower clay) compared with the burned (higher clay) site, as well as the lower C stocks at the organic-12 (lower clay) compared with the organic-4 (higher clay) site (Fig. 2). High clay content contributes to the formation and stabilization of soil aggregates (Six *et al.*, 2000; Dominy *et al.*, 2002), which results in encapsulation and protection of organic matter within those aggregates, imposing a physical barrier between decomposer microbiota and substrates and also limiting movement of water and O_2 to decomposable material (Baldock & Nelson, 2000).

When soil texture was held constant in the long-term simulations, management effects showed a large potential for restoring soil C stocks (Fig. 9), consistent with several published field studies. In general, studies of conservation systems confirm that the practice of retaining sugarcane residue (Robertson & Thorburn, 2007; Galdos *et al.*, 2009; Canellas *et al.*, 2010; Souza *et al.*, 2012; Thorburn *et al.*, 2012) and implementing organic amendments (Araújo *et al.*, 2009; Suman *et al.*, 2009; Barbosa, 2010) may increase soil organic C compared with less desirable system of preharvest burning without amendments. Increasing SOC stocks is also beneficial as a C sink for sequestering atmospheric carbon dioxide, potentially contributing to climate change mitigation (Lal *et al.*, 2007; Chan *et al.*, 2011).

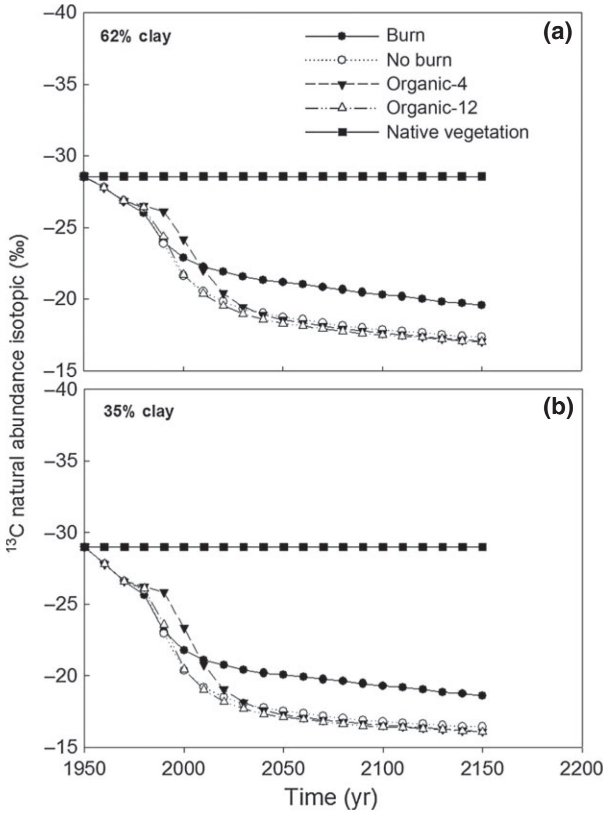

Fig. 9 Simulation until 2150 year of the natural isotopic abundance of soil (^{13}C in ‰) in the 0–20 cm soil layer for the highest clay (a) and highest sand (b) soils used in this study (Fig. 1).

Soil microbial biomass C

The highest C-MB was observed in the native forest followed in descending order by the organic-12, organic-4 and no burn sites. In general, disturbances in areas initially under native vegetation cause a substantial reduction in C-MB, particularly in Cerradão vegetation which has been shown to be one of the Brazilian biomes most sensitive to conversion into agricultural use (Kaschuk *et al.*, 2011). Our data are consistent with previous studies showing decreases in microbial biomass under conventional agricultural management, but they also show a partial recovery of C-MB under conservation management practices. Observed data showed a clear trend of increasing C-MB as a function of the amount of residue and organic matter amendments, irrespective of soil texture differences between treatment which (as previously described) impacted trends in total SOC stocks. We observed the highest results for organic sites, which corroborates with studies showing that the long-term organic inputs increase C-MB when compared with conventional management (Dominy *et al*., 2002; Fließbach *et al*., 2007; Araújo *et al*., 2009). In addition, some increase may be due to the microbial biomass contained in the organic amendments themselves (Fließbach *et al*., 2007; Araújo *et al*., 2009).

Treatment effects on the microbial biomass C were not consistently represented by the CENTURY model (Fig. 4). While there was a reasonable overall correlation between model and observed results (Table 3), the burn treatment and organic-4 treatments were overpredicted relative to the ranking of treatment sequence. Both the burn site and the organic-4 site have higher clay content, and the interaction of soil texture and residue return rate may provide an explanation for the lack of model fit to the observed data. In the CENTURY model, soil texture affects the relative stabilization of decomposition products in the active SOM pool such that higher clay + silt content increases the pool size (Metherell *et al*., 1993). Several studies have demonstrated a positive correlation among C-MB and silt and clay contents (Dominy *et al*., 2002; Robertson & Thorburn, 2007) and absorption of labile organic molecules onto clay mineral surfaces provides a mechanism of organic C stabilization against decomposition (Stotzky, 1986). However, in this case the observed data did not appear to show a strong influence of soil texture on microbial biomass C stocks, in contrast to total SOC, while texture and residue addition rate interactions were represented in the CENTURY model outcomes.

While the observed data show a strong apparent trend to organic matter addition rate, independent of soil texture, there are shortcomings and uncertainties in methods to determine soil MB (Sitompul *et al*., 1996). An important factor is that biological labiality depends not only on the physical and chemical forms of C (Duxbury *et al*., 1989), but also on interaction of the compounds of C with others constituents of soil and on environmental conditions (Motavalli *et al*., 1994; Leite & Mendonça, 2003, Cerri *et al*., 2004). In addition, there is an uncertainty associated with field sampling. Further, it has been pointed out that the active fraction in the CENTURY model represents not only the microbial biomass but also its associated metabolites (Motavalli *et al*., 1994; Parfitt *et al*., 1997) and thus may not be strictly comparable to particular assays of C-MB.

Dynamics of soil δ^{13}C and C4-derived SOC

To evaluate the performance of the CENTURY model in relation to soil δ^{13}C measured in our study, we analyzed goodness-of-fit metrics and found *r* showing a high degree of association between simulated and measured values and CD tending toward one, indicating no difference between the measured and simulated variances (Table 3). However, values for M and RMSE indicate some bias or consistent errors between measured and simulated results.

Overall, the CENTURY model tended to predict lower (more negative) δ^{13}C of total SOC compared to measured values, especially for the organic sites (Fig. 5). In general, it was expected that areas cultivated with sugarcane for a long time and, especially those that received filter cake and vinasse (as the organic sites in this study), would have a greater proportion of soil C derived from sugarcane. It is also important to note that previous pasture land use, which is dominated by C4 grasses (Fig. 2), also influenced δ^{13}C values and thus the C4 signature is a combination of current sugarcane and earlier pasture and it is not possible to separate the two influences. Cerri *et al*. (2004) and Lisboa *et al*. (2009) showed in studies involving replacement of native forest by pasture that there was an increase in C content derived from pasture, and a substitution of up to 89.5% of soil C in the top 20 cm after 80 years following deforestation.

The simulated results predicted that the burn and organic-12 sites would the largest fraction of SOC derived from C4 residues when compared with no burn and organic-4 sites (Fig. 6). These results reflect the longer period of sugarcane residue and sugarcane organic amendments input (12 years) in the organic-12 sites (relative to 4 years in the organic-4 site; Fig. 2) and the greater residue input in the unburned vs. burned site, which otherwise had a similar land use history. Interestingly, the measurement-derived estimate suggested that the proportion of C4-derived SOC in the organic-4 soil was similar to that in the unburned site, although the unburned site had been under C4 vegetation for about 20 years longer than the organic-4 site (Fig. 2). The discrepancy between the simulated and measured results for the contribution of C4 plants to SOC also may be related to the 20 cm depth that the model uses, especially in systems where such a deep litter layer makes it difficult to determine where the surface mineral soil starts.

Some studies have shown a greater contribution in no burn systems to the amount of soil C derived from sugarcane; around 50 to 60% of C was replaced after 14 years (Pinheiro *et al*., 2010) and 55 years of the sugarcane implementation (Dominy *et al*., 2002), highlighting the importance of maintaining conservational soil management.

Minimizing soil disturbance reduces the soil organic matter mineralization rate. Soil disturbance through tillage and burning processes results in reduced physical protection of soil organic matter, and therefore, increased rates of mineralization and loss of soil organic carbon (SOC). Conservational management provides physical protection of the soil surface through the input of residues and straw, retaining moisture as well as protecting the soil from erosion (Dominy *et al.*, 2002; Thorburn *et al.*, 2012).

Long-term impacts of management treatments on SOC stocks

We conducted simulations of the long-term continuation of the soil management practices described earlier to approximate the values for the steady-state under each system and how long it would take to achieve these values. In addition, we simulated the change over time of $\delta^{13}C$ with the continuing replacement of forest (C3) derived carbon with that of sugarcane (C4). These simulations were based off the same histories described above with treatments projected through to the year 2150.

In general, all simulations showed a trend of significant soil C stocks losses when the native forest was first replaced by crops. However, after sugarcane was introduced SOC stocks showed a gradual increase (Fig. 7). For the burn and organic-4 sites, having higher clay contents, simulations produced high soil C stock levels at the end of the native forest period (1950), around 22 to 25% higher soil C stocks than no burn and organic-12 sites. By year 2010, the difference in soil carbon stocks between the higher clay sites and the lower clay sites had narrowed due to the difference in management practices. By year 2150, the soil C values were spread in a pattern that reflected both differences in soil texture and the differences in management practices. The burn site simulation neared a steady-state in soil C early in the projection period. On the other hand, the high clay, high input organic-4 system never quite reached a steady-state by 2150 and approached a value for soil C that was twice that of the high clay, low input burn system. This result underlines the great impact of organic amendments when applied in soils with high content of clay and therefore a high capacity to stabilize SOC. Similarly, Smith *et al.* (1997) reported increasing SOC in a wheat experiment with farmyard manure applications even after 144 years.

The organic-12 site and the no burn site, which were similar in having lower clay content, achieved increases in soil C stocks that were intermediate between the higher clay sites. For the no burn site and organic-12 site, the final C stocks were 22 and 40% higher than the burn site and, 31 and 21% lower than organic-4 site, respectively. The organic-12 site was 14% higher in soil C than the burn site.

The simulation showed that the no burn system and the two organic systems had high potential for C recovery, in agreement with modeling studies of Bortolon *et al.* (2011) Tornquist *et al.* (2009), and Leite *et al.* (2004). Physical disturbance associated with intensive soil tillage increases the turnover of soil aggregates and accelerates the decomposition of associated SOM within aggregates, while reduced tillage increases aggregate stability and promotes the stabilization of recalcitrant SOM in micro- and macroaggregate structures. In this way, soil structure and SOC levels can act to improve soil fertility and therefore, increase plant C inputs, which can increase soil biological activity, improving the processes of aggregation (Paustian *et al.*, 2000).

In our simulations, it took decades to achieve near steady-state, with each site starting at a different level, and achieving different SOC levels depending on soil texture and managements. Similarly, Alvarez (2005), in a review of reduced tillage and no tillage systems, estimated that C sequestration would take 25–30 years to reach a new steady-state. Bortolon *et al.* (2011) and Tornquist *et al.* (2009) also found, through Century simulations, that soil C approached steady-state after a period of 150 years, although still at levels below the native condition.

The long-term $\delta^{13}C$ results showed that in the systems conservation management (no burn system and organic systems), most of the SOC would be derived from sugarcane residues by 2050, whereas the replacement of native forest SOC by sugarcane would take much longer in the burned system (Fig. 9). Dominy *et al.* (2002) observed that sugarcane residues accounted for about 61% of SOC in the top 10 cm of soil in fields conducted without burning for more than 50 years. However, Ho *et al.* (2004) observed that the amount of accumulated C derived from burned sugarcane accounted for only 25 and 22% of the soil organic C content after 50 years of cultivation (Ho *et al.*, 2004). Yoneyama *et al.* (2006) observed the contribution of C from unburned sugarcane residues after 30 year of cultivation, with the ^{13}C values varying from −21.9 to −17.5‰.

Factoring out the site differences due to soil texture, the model predicts that all three of the conservation systems would achieve SOC stocks surpassing the level in the native ecosystem, whereas with conventional management, including burning, SOC stocks would be about 60% of the amount under native vegetation, irrespective of the soil texture (Fig. 8). The two main agricultural practices that impact soil C stocks in Brazil are the tillage and cropping system (Bayer *et al.*, 2011) and several sugarcane studies have shown decreasing SOC stocks over time due to burning practices (Dominy *et al.*, 2002; Galdos *et al.*, 2009; Thorburn *et al.*, 2012), where burning reduces the amount of biomass added to the soils and accelerates mineralization/decomposition rates. SOC stocks for any given management practices were projected to be higher in soils with higher clay content, within the range of soil textures represented by the field sites (Fig. 8). This is consistent with studies by Tornquist *et al*. (2009), Bricklemyer *et al*., (2007), Dominy *et al*. (2002) and others, showing that clay and silt content are principal factors determining the capacity of soil to stabilize SOC (Hassink, 1997; Six *et al*., 2002; Bayer *et al*., 2011). Sandy soils have less capacity for protection and high unprotected C content (Plante *et al*., 2006), in part because the protection of particulate organic matter within aggregates is favored at higher clay content (Balesdent *et al*., 2000; Bayer *et al*., 2011). Also soils with predominantly variable charge clay minerals have lower organic matter decomposition rates of organic matter that are less altered by tillage as compared to sandy soils (Hassink, 1997; Bayer *et al*., 2011).

We can conclude that conservation management systems such as returning residues to the soil rather than burning them, together with other organic matter additions can substantially increase SOC stocks in the long term compared to conventional systems where preharvest burning is used and that soil texture strongly influenced capacity of soils to accumulate C. Our results generally supported the use of CENTURY model for assessing SOC dynamics in sugarcane under different soil managements, as an aid in determining the most appropriate soil management strategies for different edaphoclimatics conditions. Considering that monitoring changes in soil C stocks by repeated measurements is expensive and the experimental duration required to detect changes in SOC is usually long and varies with many factors, modeling of soil C is a feasible and cost effective option.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table 1. Goianésia climatic data used in the site file to run Century.
Table 2. Supplemental table with default/modified Century parameters of cultivation (cult.100).
Table 3. Supplemental table with default/modified Century parameters of harvest, fire and crop.
Table 4. Description of organic residues from sugarcane and their representation in Century (parameters in omad.100).