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REGULAR ARTICLE

Modelling SOC response to land use change and management practices in sugarcane cultivation in South-Central Brazil

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Abstract
Background and aims To study the impact of land use change (LUC) from native vegetation and pasture to sugarcane cultivation as well as to evaluate the effect of different management practices on long-term SOC dynamics using the CENTURY ecosystem model.
Methods A soil data set of 85 study areas including sugarcane, pasture and annual crops from eleven counties distributed over the south-central region of Brazil was used for model validation and three future scenarios of sugarcane management were simulated: i) green harvesting (SC1); ii) green harvesting plus organic amendments (SC2) and iii) green harvesting plus low N inputs (SC3). Sugarcane harvest with burning was simulated as the baseline system (SCB).
Results The model performance was good ($R^2 = 0.79$) in replicating measured C stocks as well as reflecting the main trends of C stock changes due to LUC. Long-term simulations suggested that changes in the sugarcane harvest from burning to green harvesting would increase soil C stocks by an average of 0.21 Mg ha^{-1} year^{-1}. The potential of C accumulation was projected to be higher when vinasse and filter cake are added to the soil, varying between 0.34 and 0.37 Mg C ha^{-1} year^{-1} in SC3 and SC2 respectively.
Conclusions The Century model can be used as tool to study the impact of different soil managements in the SOC dynamics in sugarcane. C losses due to the conversion from pasture to sugarcane can be totally restored after 24, 17 and 18 years under SC1, SC2 and SC3, respectively.

Keywords Soil carbon · Ethanol · Green harvesting · Century model · Organic amendments · *Saccharum spp.*

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Introduction

Sugarcane is an important component of the Brazilian economy, supporting about 1.5 % of the Gross Domestic

Product. Currently, more than 50 % of the sugarcane crushed in Brazil is distilled into ethanol (Conab 2013), one of the most sustainable biofuels currently produced at commercial scales and whose growing demand has caused considerable increases in the sugarcane planting, which reached 10 million hectares during the last harvest season (Conab 2013).

Future projections of the sugarcane sector aim to increase ethanol production to 58.8 billion liters in the next 5 years, a value that corresponds to more than twice the yield registered in the year 2014. To achieve those national goals the planted area for sugarcane would need to nearly double, to 19 million hectares (Conab 2015; Cerri et al. 2010).

Although this expansion would increase the amount of ethanol available to substitute for fossil fuel, land use change (LUC) can affect the greenhouse gas (GHG) balance of the sugarcane crop and consequently the overall sustainability of the biofuel. The effects of LUC during the transition to sugarcane production can lead to decreases in soil carbon stocks (Mello et al. 2014; Fearnside et al. 2009) and increases in atmospheric GHG emissions.

Studies indicate that energy crops expansion into native and agricultural land uses can result in a transient "carbon debt" (Fargione et al. 2008; Mello et al. 2014). In Brazil, the GHG emissions due to LUC from native vegetation and pastures to sugarcane could result in net transitional soil carbon (C) losses with payback times ranging from 17 years in native vegetation and 5–6 years in pastures (Mello et al. 2014). In contrast, when sugarcane replaced annual cropland, soil C stocks increased by 17 % in the 0–30 cm depth layer, since in croplands residue inputs are lower and tillage operations are performed annually, resulting in greater C losses (Mello et al. 2014).

Conservation management practices in sugarcane can contribute to the C restoration lost through land cultivation, diminishing the negative impacts of LUC processes. The conversion from manual harvesting with pre-harvest burning to mechanical or green harvesting retains considerable quantities of dry matter on the soil surface which provides several benefits (Ceddia et al. 1999; Graham et al. 2002; Tominaga et al. 2002; Razafimbelo et al. 2006; Hartemink 2008; Luca et al. 2008; Razafimbelo et al. 2006; Hartemink 2008; Luca et al. 2008), among which soil C accumulation is highlighted (Canellas et al. 2003; Robertson and Thorburn 2007; Galdos et al. 2009a; Thorburn et al. 2012). Furthermore, organic matter amendments such as vinasse and filter cake, residues from the industrial sugarcane processing which are typically applied to sugarcane fields, can increase soil organic carbon (SOC) contents and enhance soil quality and crop production (Fließbach and Mäder 2000; Canellas et al. 2003; De Resende et al. 2006; Zolin et al. 2011; De Souza Barros et al. 2013; Da Silva et al. 2014).

In addition to management impacts, soil organic matter is also affected by soil characteristics (e.g., texture and mineralogy) and climate conditions. The potential of a given soil to store C is highly variable and difficult to predict because of the many complex interactions governing soil C dynamics (Tornquist et al. 2009). To this end, mathematical modelling of soil biogeochemical processes is a valuable tool for improving our understanding of the role of tropical land use and soil management in soil organic matter and nutrient dynamics. Prediction of future agroecosystem states are important aspects of model application (Krull et al. 2003) which can aid decision makers and planners in developing sustainable soil management systems, thereby insuring appropriate GHG mitigation measures.

In this study we used the Century model to assess the impact of LUC related to sugarcane expansion in south-central Brazil, as well as to evaluate the effect of different management practices on long-term SOC dynamics. The Century model is an ecosystem-level model of the plant–soil system that simulates carbon and nutrient dynamics (Parton et al. 1987; Metherell et al. 1993). Although it was originally developed for modelling soil nutrient dynamics in grassland systems, it has been subsequently modified and expanded to include annual crops, pasture, savanna and forest systems (Parton and Rasmussen 1994; Kelly et al. 1997; Peng et al. 1998; Kirschbaum and Paul 2002). Several previous applications of the model have been made for different ecosystem types in tropical and subtropical conditions in Brazil (e.g., Cerri et al. 2004; Leite et al. 2004; Galdos et al. 2009b; Tornquist et al. 2009; Bortolon et al. 2011; Brandani et al. 2014).

Material and methods

Study region, land use and soil management

The study area involved eleven counties spanning the south-central region of Brazil (Fig. 1) which is the main

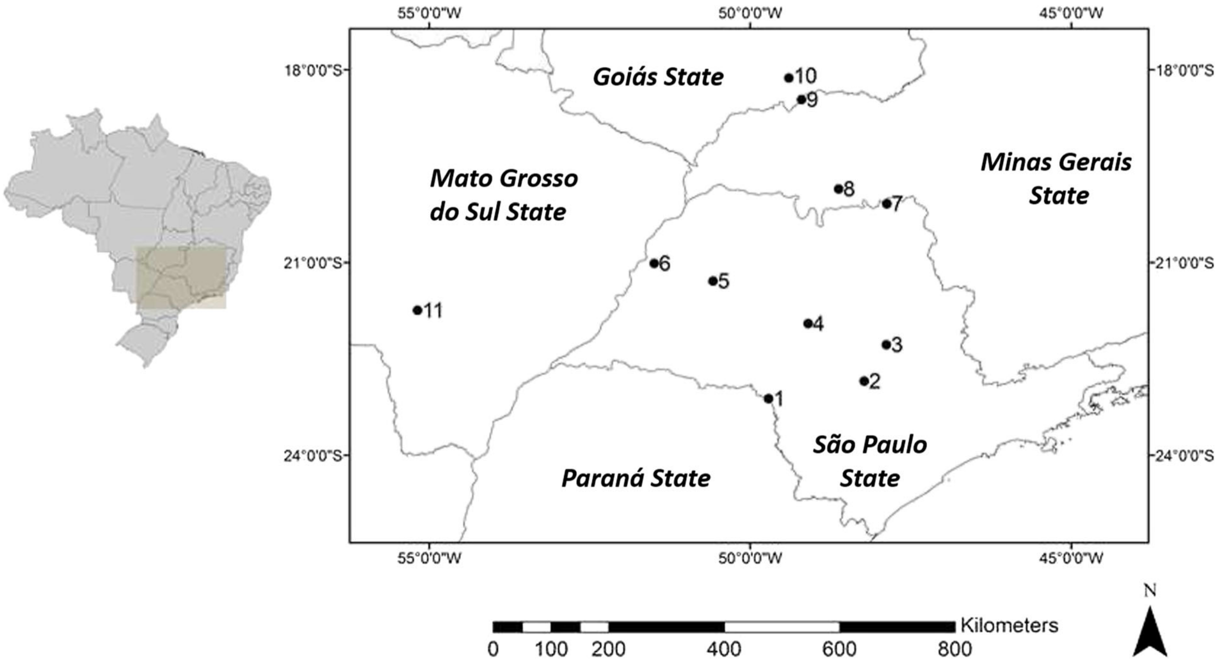

Fig. 1 Sampling areas in south-central Brazil selected for modelling of soil C dynamics: Counties in Sao Paulo state (1–7), Minas Gerais state (8–9), Goias state (10) and Mato Groso do Sul state (11)

area of sugarcane production (79 % of total Brazilian production in 2011/2012 season) and covers approximately 30 % of the national territory. The climate of this large region varies, encompassing three major climate types: i) tropical moist (Aw, Koppen) with dry winters, precipitation events during the summer season and average monthly temperatures greater than 18 °C; and ii) moist subtropical climate covering subtropical without a dry season (Cfa, Cfb Koeppen), with precipitation well distributed over the year, and iii) subtropical with a dry winter (Cwa, Cwb Koeppen) and warm or hot summers with heavy precipitation during the summer.

The complexity of landforms, climate, and geology in the central south region results in a wide variety of soils. The Oxisols, highly weathered soils composed mainly of kaolinite, iron and aluminum oxides, cover 52 % of this area. Ultisols and Entisols cover 17 % and 14 % of the south-central region (Manzatto et al. 2009).

The predominant native vegetation is the Brazilian tropical savanna, known as Cerrado, and the Atlantic Forest. The Cerrado is a tropical ecosystem consisting of a diverse mosaic of grasslands, savannas, woodlands and forests (Coutinho 1978). According to Sano et al. (2010) the Cerrado *sensu stricto* is the dominant remnant vegetation cover in Cerrado, accounting for 61 % of the total native vegetation. This phytophisionomy is characterized by high species richness of shrubs and trees with mean height of about 3–6 m and tree cover of 20–50 % (Ribeiro et al. 1998), which is often burned, either naturally or as part of a management cycle. Eiten (1975) estimated the average frequency of fire set by indigenous people of the Cerrado in Mato Grosso, Brazil, to be 3–5 years.

The Atlantic Forest is a dense ombrophilous forest with several subdivisions, including coastal (3 to 50 m), submontane (50 to 500 m), montane (500 to 1200 m), and high montane (1200 to 1400 m) forests, creating a vegetation gradient ranging from shrubs to well-developed montane forest (De Gusmão 2003).

Both the Cerrado and the Atlantic Forest ecosystems have been the object of land cover changes. Cultivated pastures (mostly *Brachiaria spp.*) and cropping systems are the dominant anthropogenic landscapes in the Cerrado, occupying 26.5 % and 10.5 % of the land area, respectively (Sano et al. 2008). Traditionally, with conversion from native vegetation to pasture, pastures are established after clearing and burning without chemical fertilization before planting. According to Junior and Vilela (2002) more than 70 % of sown pastures in Brazil suffer some degradation and most of them show an advanced stage of degradation, which is caused by bad establishment of swards, poor maintenance and inadequate management.

Due to the recent increases in the demand of ethanol and the edaphic-climate suitability of the central-south region, pastures are being replaced by sugarcane. Statistics of sugarcane production indicated that more than 75 % of the expansion of sugarcane in that region during the 2008/2009 and 2009/2010 crop seasons occurred on pastures (Conab 2010, 2012).

Sugarcane is an annual crop, which is commercially cultivated in monoculture with a full crop cycle of six years, during which five harvests, four ratoon treatments, and one field renovation are performed (Macedo et al. 2008). Traditionally, the tops and leaves are burned before the harvest in order to facilitate this operation. However, due to legal restrictions implemented recently in Brazil, burning has decreased significantly with the implementation of green harvest systems, where large quantities of residues are left on the soil surface, providing several potential benefits to the system. According to National Supply Company (Conab - Acronym in Portuguese), 64 % of the total harvested area in the 2011–2012 crop season involved mechanical harvest without burning (Hartemink 2008), and this trend will continue in order to improve the environmental aspects of sugarcane production and to respond to global market politics.

Evaluation of land use/land cover change impacts

The site-level data used in this study were reported by Mello et al. (2014) and involved 108 study areas. Of this total number, 63 areas correspond to sugarcane crop areas, where this land use replaced either pastures (55), cropland (5) or native vegetation (3); 32 areas correspond to pastures, five areas of cropland and eight areas of native vegetation; which were used by the authors as comparison pairs (Online Resource 1).

According to Mello et al. (2014) the selection of the study areas and site comparison pairs was based on historical land use information, availability of reference areas (pasture, annual cropping or natural vegetation) older than 20 years with similar geomorphic characteristics (topography, soil type) and adjacency to the sugarcane sites.

In this study, data from all the native vegetation areas as well as eight sugarcane areas, six pasture areas and one cropland area were used for model parameterization. The remaining study sites.

The Century ecosystem model

We used the Century model version 4.6 to simulate changes in soil C contents in the 0–20 cm layer due to sugarcane crop cultivation (Parton et al. 1987; Metherell et al. 1993). Century simulates ecosystem dynamics of C, N, P and S and is comprised of different submodels including soil organic matter (SOM) formation and decomposition, soil water balance and primary production of crops, grassland and forest systems. In this application, we used the C and N version of the model.

The SOM sub-model includes five pools, two of which represent litter and three comprise the SOM. Plant and animal residues (litter) are divided into structural and metabolic pools as a function of the lignin:N ratio. The SOM is divided into three pools with different potential decomposition rates: i) Active pool, which represents microbial biomass and metabolites which turn over relatively rapidly (annual time scales); ii) Slow pool consisting of partially stabilized SOM constituents with an intermediate turnover time (on the order of decades), and iii) Passive pool, which represents recalcitrant materials that turn over on time scales of centuries. Further information about the Century model is described in Metherell et al. (1993) and Parton et al. (1994).

Model Initialization and Parameterization

Initialization of the model included specifying site-specific soil and climate characteristics, where soil physical properties (i.e., sand, silt, and clay content, bulk density, soil depth and pH) were taken from measurements at each site (Mello et al. 2014) and climate inputs (i.e., monthly precipitation and mean, maximum and minimum monthly temperatures) were taken from the meteorological station closest to each site, with data provided by *Agrometeorological Monitoring System* (AGRITEMPO).

To represent specific attributes of the different ecosystems in our analysis, we estimated several parameters that affect primary productivity, dry matter allocation and disturbance regimes, to calibrate the model against representative observations in the literature:

1. Forest calibration

To initialize the model prior to simulating forest clearing and pasture and/or sugarcane establishment, we used the Century forest submodel to estimate equilibrium organic matter levels and plant productivity under native forest conditions, over a 6000-year simulation period.

Two kinds of native vegetation were simulated: The cerrado *sensu stricto*, which was parameterized as a savanna, and the Atlantic forest. For cerrado *sensu stricto* we used biomass data from Abdala et al. (1998) and De Castro and Kauffman (1998) to initialize the biomass allocation parameters in the forest growth model. The C:N ratio in each forest compartment was adjusted according to the data reported by Lilienfein et al. (2001); the monthly senescence rate for leaves was calibrated as the average of the values quantified by Valenti et al. (2008) and Silva et al. (2007) and the lignin content in leaves and wood were set at 29.6 % and 26 %, respectively (Silva et al. 2007; Do Vale et al. 2010).

Since atmospheric N deposition and biological N fixation rates have a significant influence on steady-state native soil carbon stocks, we set those parameters to the typical values for this ecosystem: 0.5 g m^{-2} $year^{-1}$ for N atmospheric deposition (Bustamante et al. 2012) and 0.002 g m^{-2} $year^{-1}$ of N per gram of C produced for N biological fixation (Grace et al. 2006; Bustamante et al. 2012). For all other parameters, the default values specified for Century 4.6 were used.

Two natural disturbance events were assumed in the Cerrado equilibrium simulation, a fire event occurring once every 5 years (De Castro and Kauffman 1998) which causes losses of 33 % of aboveground biomass as reported by De Castro and Kauffman (1998) and a tree mortality and subsequent tree-fall and gap formation event every 120 years, after which the aboveground biomass returns to the system as litter and wood residues (Cerri et al. 2004).

The simulation of Atlantic forest was performed using one of the Century default tropical forest parameter sets that also includes tree mortality and subsequent tree-fall and gap formation every 120 years.

After simulating the equilibrium condition in native vegetation, the model was set to simulate the deforestation process following the slash and burn procedure. Those events were parameterized according to the calibration performed by Cerri et al. (2004).

2. Pastures and Annual crops

To adjust the model for pasture conditions we used the biomass productivity data reported by Lilienfein and Wilcke (2003). In order to simulate grazing management, we specified the moderate grazing option during each month, which corresponds to an average stocking rate of 1.5 cattle ha^{-1}.

For cropland conditions we adjusted the potential monthly crop production to reach mean values of 14.2 and 6.3 Mg ha^{-1} of aboveground biomass in corn and soybeans respectively, the average of productivity found in studies in the region (Walter et al. 2009; Bordin et al. 2008; De Castro Gava et al. 2010; Guareschi et al. 2010; Bergamaschi et al. 2013); Finoto et al. 2012; Simon 2009). For all other parameters, the default values specified for Century 4.6 for pasture and cropland were used.

3. Sugarcane crop

The sugarcane crop, as a perennial crop, was simulated using a modified tree submodel as done in previous work on sugarcane (e.g., Galdos et al. 2009b) which allows parameterization of the aboveground productivity for each of the plant parts (leaves, tops and stalk).

The optimum and maximum temperature for production were set at 30 °C and 45 °C respectively (Galdos et al. 2009b). The distribution of aboveground and belowground biomass was calibrated based on data obtained from biometric measurements reported by Silva-Olaya (2014) and data from Faroni (2004); Otto et al. (2009); Leite (2010) and De Oliveira et al. (2011).

The C:N ratio and lignin content of each plant part were adjusted according to data found in vegetation samples collected in three areas of sugarcane planting – involving the same sugarcane variety (RB86–7515) and similar soil, climate, topography and management – near Piracicaba, in northeastern São Paulo State, Brazil. Determination of C and N concentration in sugarcane tissues for C:N ratio were performed by dry combustion in a LECO CN-2000. Lignin content was determinated according to Van Soest et al. (1991).

The potential biological N fixation rate was specified as reported by Galdos et al. (2009b). The monthly death rate was obtained from Vallis et al. (1996). For all other parameters the default values were used.

Two types of harvest systems in sugarcane were simulated based on standard management practices: i) manual harvest preceded by burning of the dry leaves and tops, and ii) mechanical harvest or green harvesting where the leaves, tops and a small fraction of stalks are retained in the field, forming a thick mulch on soil surface. Both harvesting systems were calibrated in the Century model according to the parameters included in the "trem.100", which controls the surface organic material removal and the nutrient cycling as affected by fire or harvest events.

The impact of fire on the vegetation and litter was based on field experiments with controlled pre-harvest fires reported by Ballcoelho et al. (1993); Basanta et al. (2003) and Marques et al. (2009), where 90 % and 41 % of dry matter in the litter and tops fractions, respectively, were removed by the fire. After burning, the partially burned tops are separated from the stalks and left on the field. The quantity of N which returns to the system after the fire was set at 36 %, the mean value found in those studies.

In the green harvesting system, the model was set to remove 99 % of aboveground biomass, with 94 % of dry matter in tops and leaves and 2.8 % of stalks returned to the system as litter after the harvest. Those percentages were established based on data of residues from mechanical harvest reported by one of the mills where the soil samples were collected.

The root dynamics associated with sugarcane production from initial planting through several ratoon stages are poorly understood. Some studies have stated that after the first sugarcane harvest the original root system quickly becomes non-functional and is fully replaced by new root growth (Baver et al. 1962). However other studies reported that part of the root system remains active after the harvest of stalks (Wood and Wood 1967; Glover 1968; Ballcoelho et al. 1992). For the model parameterization we assumed that 60 % of the sugarcane root system dies after the harvest, based on calculations performed from data reported by Otto (2012).

According to reported management histories, some of the study areas had organic amendments during the sugarcane production cycle. Residues from the processing of sugarcane into sugar and ethanol, as filter cake and vinasse, are typically applied in certain regions as organic matter amendments. The effects of those amendments were modelled through the "omad.100" functions in Century, in which the timing, rate, and composition of the residue applied were set based on the model calibration of Galdos et al. (2009b).

Soil tillage, which is performed every 5 to 6 years when the sugarcane field is renovated due to decreases in the yield, was simulated using the "intensive" default tillage parameters specified in Century 4.6.

Model Validation

We evaluated model performance by comparing model results to measured total SOC for a data set composed of 85 study areas, which were not used in the parameterization phase. Measures of goodness-of-fit were taken from Smith et al. (1997), including: sample correlation coefficient (r), coefficient of determination (CD), root mean square error (RMSE), and mean difference between observations and simulation (M).

Future scenarios and long-term soil C stock prediction

According to Conab (2008, 2013) the planted area of sugarcane has increased by 2.9 million hectares from 2006/2007 to 2011/2012. More than 95 % of that expansion has occurred in the southcentral region of the country, with 70.8 % and 17.5 % of new sugarcane land derived from pasture and annual crops production, respectively. According to Nassar et al. (2008) the sugarcane area is expected to reach a level of 11.7 million hectares by 2018, following the trend of LUC observed in the past, where pastures were the main land use replaced by sugarcane.

Regarding the harvest system, the data from Conab (2013) showed an increase in the adoption of green harvesting in the south-central region, from 28.6 % to 71.6 % during the last six harvest seasons. In Sao Paulo state, the main state producer of sugarcane, State Law No. 11.241/2002 prescribed cessation of sugarcane burning by 2021 in mechanized areas (with slope < 12 %) and by 2030 for all areas of sugarcane production. Despite a lack of legal restrictions on sugarcane pre-harvest burning in other states of Brazil, survey data show a decrease in this practice during the past years in the states of Parana, Minas Gerais, Matto Grosso and Goias, averaging 52 %.

Based on these trends and the legal requirements in Sao Paulo state, a series of 50-year projections of different management systems and variable levels of green harvesting were generated to assess the impact on the long-term soil C dynamics at each site. The conventional sugarcane harvest system with burning was used as the baseline system (SCB) for comparisons.

Considering that sugarcane expansion is projected to occur mainly over pastures areas, the long-term soil C changes were simulated for the study sites involving this land use transition. To standardize the land use histories for the future scenarios, we used the mean year of establishment and time under pasture observed at the study sites to start the simulations. The simulation of future scenarios of management in the sugarcane crop commenced first after simulating an 11-year period of burning with harvest, which was the mean number of years involving this practice in all the study sites where this kind of land use transition was performed.

Simulated future scenarios:

1. Green harvesting (SC1): The adoption of green harvesting system in sugarcane crop, where the leaves and tips are retained in the field was simulated. Currently, more than 70 % of the harvested area in the south-central region and 60 % of the harvested area in the country involve this kind of harvest (Conab 2013). For the simulation of this scenario, an N fertilization rate of 40 kg N ha^{-1} for plant year cane and 100 kg N ha^{-1} for ratoon cane was used.
2. Green harvesting + OMAD (vinasse and filter cake) (SC2): Organic amendment inputs such as vinasse (a liquid) and filter cake were simulated for all the study areas. Typical application rates of those residues in Brazilian sugarcane fields: 205 m^3 ha^{-1} year^{-1} of vinasse and 9 Mg dry matter ha^{-1} of filter cake at cane plantations during reformation periods, were assumed for this scenario.
3. Green harvesting + Low N inputs (SC3): Studies conducted in Brazil and Australia have highlighted the potential to reduce N fertilization rate in the ratoon cane with adoption of green harvesting (Vallis et al. 1996; Robertson and Thorburn 2007; Trivelin et al. 2013). According to Trivelin et al. (2013), 30 years after the implementation of the green harvesting system, there is a potential reduction of N fertilization of 36 kg ha^{-1} year^{-1}. For plant sugarcane, Nunes Júnior (2005) suggested that the application of 5 Mg ha^{-1} of filter cake could supply 100 % of N needs of the crop. On this basis, we simulated lower mineral and organic N inputs for this scenario: 5 Mg N ha^{-1} of filter cake (with no N fertilization) in planted cane and 70 kg N ha^{-1} year^{-1} of mineral fertilizer in ratoon cane.

Once the long-term projections of sugarcane management effects were performed, we grouped the study areas (validation sites) according to the classification of suitability proposed by the Sugarcane Agro-ecological Zoning in Brazil (ZAE), which identified eight classes of suitability ranging from high priority suitability to unsuitable (due to the weather and/or soil conditions) (Manzatto et al. 2009). Subsequently, the mean C stocks for the classes of suitability covered by the data set were estimated. Only two study points were located in areas classified as unsuitable due to climatic restrictions related to possible frost conditions, so those data were not reported Finally we grouped the soils according to the textural classes according to the Brazilian Soil Classification system (Embrapa 2006).

Results

Model performance

The model estimates were consistent with the field-observed SOC stocks and the range of cross-site SOC levels in all systems of production, pastures areas as well as annual crops and sugarcane areas (Fig. 2). The mean difference between measured and simulated SOC stocks was 3.17 Mg C ha^{-1} in sugarcane and −0.37 Mg C ha^{-1} and 1.73 Mg C ha^{-1} in pastures and annual crops. The maximum deviations between the measured and simulated data for an individual site were 14.0, 11.6 and 21.0 Mg C ha^{-1}, for pasture, annual crops and sugarcane, respectively.

The results from statistical tests indicate that the model performance was good in simulating measured C stocks (Table 1). The coefficient of correlation (r) between measured and simulated data was >0.85 for all the systems simulated, indicating a strong positive degree of association between simulated and measured values and relatively little bias. The coefficient of determination value (CD) shown demonstrates that much of the total variance of the observed data was explained by the model.

The values found for root mean square error (RMSE) indicate a moderate difference between measured and simulated values. According to the modelling efficiency (EF) determined, the simulated values describe the trend in the measured data substantially better than the mean of the observations.

In addition to the cross-site validations of the model for point measurements of SOC stocks, we assessed the model's representation of changes in SOC stocks over time for each site. According to the model, the conversion from native vegetation to pastures resulted in mean rate of C losses of 0.19 Mg ha^{-1} year^{-1}, a value lower

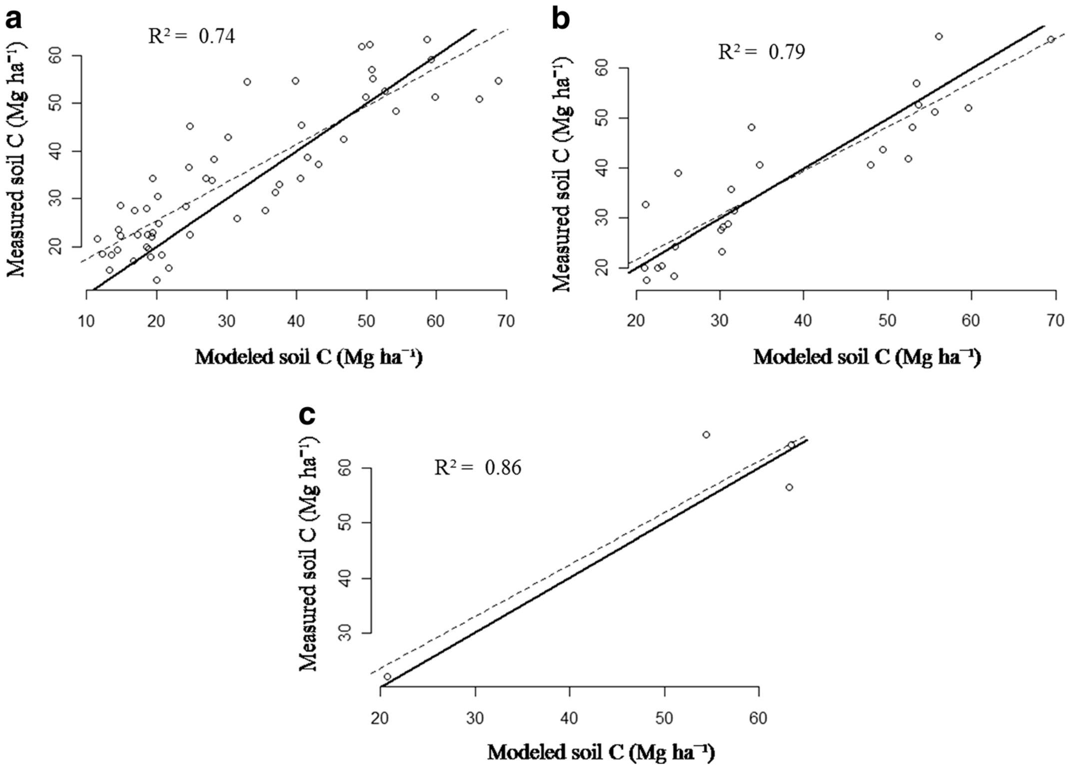

Fig. 2 Measured versus simulated soil C stocks in sugarcane (**a**), pasture (**b**) and annual crops (**c**) conditions, with coefficient of determination shown for each system

than that found when annual crops are established after clearing native vegetation (1.14 Mg C ha^{-1} year^{-1}). With secondary land use conversions to sugarcane, the model predicted that conversion from pasture would yield a mean soil C loss rate of 0.49 Mg ha^{-1} year^{-1}. The opposite trend (C accumulation) was observed when sugarcane was established on land used for the production of annual crops (average increase of 0.10 Mg ha^{-1} year^{-1}).

Table 1 Statistical tests applied for agreement between simulated and observed values of the sugarcane, pasture and annual crops sites

Statistical parameters	Sugarcane	Pasture	Annual Crops
r = Correlation Coeff.	0.86	0.89	0.93
RMSE = Root mean square error of model	24.79	17.71	12.98
RMSE (95 % Confidence Limit)	22.75	20.62	25.76
EF = Modelling Efficiency	0.63	0.78	0.85
EF (95 % Confidence Limit). Best = +1	0.70	0.70	0.42
CD = Coefficient of Determination. Best =1	0.81	0.98	1.01
M = Mean Difference	3.17	-0.37	1.73
E = Relative Error	9.15	3.21	3.17
E (95 % Confidence Limit).	21.27	18.10	24.55
Number of Values	55	26	4

Long-term Soil C stock prediction

Changes in the soil C stocks through the transition from native vegetation to pastures and then 50 years of sugarcane crop involving different scenarios of management are presented in Fig. 3. Soil C stocks in all the land use systems simulated were higher in clayey soils, with greater values in the areas located under regular suitability classes (Fig. 3).

Results from the long-term simulations showed a mix of C losses (negative values) and gains for all suitability classes (Table 2). The change in the harvest system from pre-harvest burning to green harvesting increased C stocks on average by 0.21 Mg ha^{-1} year^{-1}, but values varied as a function of clay content. The potential C accumulation was even greater when the production of sugarcane included organic amendments.

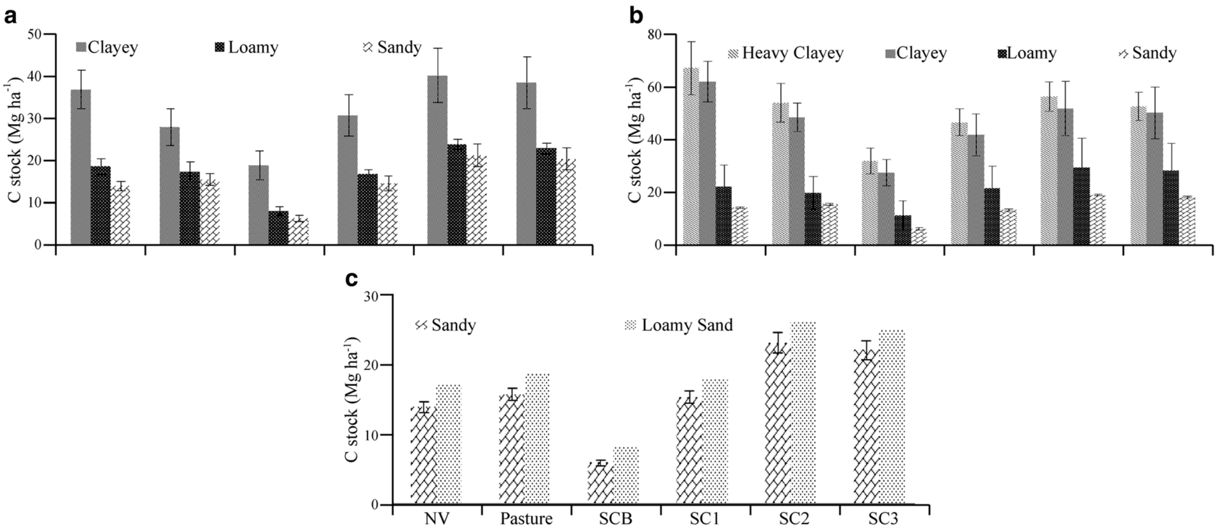

Fig. 3 Projections for soil C stocks (0–20 cm depth) in native vegetation (NV), pasture and different scenarios of sugarcane crop management (SCB –Sugarcane pre-harvest burning; SC1 - Green harvesting; SC2 -Green harvesting + OMAD; SC3 - Green harvesting + Low N inputs) in south-central Brazil. **a** Areas under pasture with priority or high suitability; **b** Areas under pasture with regular suitability and **c** Areas under pastures with low suitability

By analyzing the soil C dynamics over the time for all projections we estimated the mean number of years it would take for sugarcane planting to offset the soil C losses caused by the LUC from pasture (time span for soil C restoration). With the SC1 scenario, C stocks reached the preconversion levels in only two soil textural classes: clayey and loamy under priority and regular suitability respectively (Table 3). For scenarios with organic amendments to sugarcane, (SC2 and SC3) allows for reduction of the time-span for soil C recovery by 29 % in clayey soils and 25 % in loamy soils. In other textural classes changing the harvest system is not enough to recover the losses of soil C following LUC.

Discussion

Total Soil C dynamics simulation

The Century model was able to replicate measured C stocks as well to reflect the main trends of C stock variation due to land use changes (Fig. 2). The statistical analysis of the performance of the modelling showed the accuracy of the simulations (Table 1).

The simulated quantities of soil C stock in pasture and annual crops fit the measured data well (R = 0.89 and 0.93 respectively). Significant bias towards over- or under-estimation was not detected in the simulations when compared to measured values. Although some simulated points lay outside the standard errors of individual measured values in pasture and annual crops, the RMSE values are lower than the RMSE (95 %) values indicating that they fell within the 95 % confidence interval for the whole dataset.

In sugarcane, the model performance was good in replicating measured soil C stocks with r and CD values close to one, which indicates that much of the total variance of the observed data was explained by the model. However, the RMSE value for soil C under sugarcane was higher than in pasture and annual crops, lying outside the 95 % confidence interval of the measured data. Bias in the distribution of predicted values with respect to measured values was not detected since E value was lower than E95%.

Although we did not have aboveground plant productivity measurements for the study areas, we compared the average simulated stalk yield (96 Mg ha^{-1}) with mean yields reported for the last five harvesting seasons in south-central Brazil (ca. 80 Mg ha^{-1}) (Conab 2013). The model predicted somewhat higher

Table 2 Soil C stocks changes as a function of transition from pasture to sugarcane involving pre-harvest burning (P – SB) and from pre-harvest burning to different scenarios of conservation management(SB – SC1, SC2, SC3) in each class of suitability for sugarcane expansion in south-central Brazil

Texture	Priority suitability			
	Transitions			
	P – SB	SB - SC1	SB - SC2	SB - SC3
Mg ha^{-1} year^{-1}				
Clayey	-0.18	0.25	0.44	0.41
Loamy	-0.19	0.18	0.33	0.31
Sandy	-0.19	0.17	0.31	0.29
Regular suitability				
Heavy clayey	-0.43	0.29	0.48	0.41
Clayey	-0.41	0.28	0.48	0.40
Loamy	-0.17	0.18	0.33	0.31
Sandy	-0.18	0.14	0.25	0.24
Low suitability				
Loamy sand	-0.20	0.19	0.35	0.33
Sandy	-0.21	0.20	0.36	0.34

yields, suggesting either that the study sites simulated were on average more productive than the regional average and/or that previous calibrations of the sugarcane submodel in Century were done using data from higher productivity sites.

Table 3 Time span (years) for soil C restoration to the level before conversion from pasture to sugarcane

Texture	SC1	SC2	SC3
Prioriry suitability			
Clayey	24	17	17
Loamy	N/A*	18	24
Sandy	N/A	24	24
Regular suitability			
Heavy clay	N/A	40	40
Clayey	N/A	40	40
Loamy	24	18	18
Sandy	N/A	24	24
Low suitability			
Loamy sand	N/A	24	24
Sandy	N/A	24	24

*N/A means times span greater than simulated

The trend of SOC stocks over the time was also replicated by the model. Although measured C stocks under native vegetation were not available for each site, we verified that the C stocks simulated in the equilibrium condition (i.e., under native vegetation) were higher than those found in pastures and annual crops, decreasing over the time as a function of the management practices simulated at each site. Native forest had higher C stocks compared to the soil under agricultural use in both measured and modeled results. All studies that focused on the eects of land conversion from forest to cultivated land indicated that LUC induces a reduction of the available soil C and a decrease in its quality (Batlle-Aguilar et al. 2010). In tropical soils the soil C can be reduced by up to 50 % in the first years of cultivation due to several processes, including microbial decomposition and erosion (Mielniczuk et al. 1999).

The rate of losses is influenced by the type of native vegetation, climate, soil and management practices (Davidson and Ackerman 1993; Bruce et al. 1999). The conversion from forest to pasture land can lead to either a positive or negative impact on soil C stocks. In a literature review, Cerri et al. (2006) found that soil C stocks of two-thirds of the pastures studied increased in comparison to native vegetation in the Amazon region whereas one-third showed decreased SOC levels. Increases in the soil C by 2.7 to 6.0 Mg ha^{-1} year^{-1} have been reported in well-managed pastures in Amazonia (Demoraes et al. 1996; Bernoux et al. 1998; Cerri et al. 2003). In our study the model predicted mean annual C losses of 0.19 Mg ha^{-1} when pastures are established after clearing the native vegetation, averaged over 29 years following conversion. Those results are in line with the range in reductions in SOC stocks from 0.15 to 1.89 Mg ha^{-1} year^{-1} observed in Brazilian pastures involving Amazon Forest and Cerrado vegetation conversion (0–30 cm depth) (La Scala et al. 2012). According to Maia et al. (2009), the variation in the C content is affected by the pasture management as well as by the soil type, since C depletion is observed in non-degraded pastures on Oxisols (0.03 Mg ha^{-1} year^{-1}) but C accumulation can occur under other types of soils, mostly Ultisols (0.72 Mg ha^{-1} year^{-1}). Braz et al. (2013) and Carvalho et al. (2010) also found similar results with lower C stocks under degraded pastures and higher C stocks in well managed pastures in the Cerrado region.

The degradation of pastures in the Brazilian Cerrado is an important problem which threatens the sustainability of Brazilian livestock production. More than 70 % of the total areas under cultivated pastures show some degree of degradation (Martha Junior and Vilela 2002; Batlle-Bayer et al. 2010) due to poor management. Generally, after a few years of pasture establishment, stocking rates are increased without implementing maintenance fertilization, which leads to a rapid decline of nutrients in the soil (Nair et al. 2011). Under these conditions lower quantities of plant litter and organic matter light fraction, important pools in nutrient cycling, are observed (De Oliveira et al. 2004).

The modelling results of conversion to annual crops indicated soil C losses averaging 1.14 Mg ha^{-1} year^{-1}. Conversion from native vegetation to annual crops is typically observed to reduce soil C stocks, however the magnitude of those losses is strongly influenced by management practices and the type of crop cultivated (Bayer et al. 2006; Dolan et al. 2006). The annual rate of C decrease predicted by the model was consistent with the average of values from previous studies in the Brazilian Cerrado region (Jantalia et al. 2007; Carvalho et al. 2010), although higher than some studies that report minimal soil C losses from conversion to annual crops (Bayer et al. 2006; Marchão et al. 2009; Figueiredo et al. 2013). In the simulations for our sites, conversion to annual crops involved long-term (~10 years) continuous soybean cropping with conventional tillage, resulted in lower C input and higher mineralization rates than in the native soil condition.

Regarding the sugarcane planting, the Century model indicated different trends in SOC as a function of the previous management. Conversion from pastures to sugarcane caused a mean rate of soil C depletion of 0.49 Mg ha^{-1} year^{-1}, meanwhile conversion from annual cropland to sugarcane resulted in C accumulation averaging 0.10 Mg ha^{-1} year^{-1}. Those C losses in sugarcane areas established over pastures can be explained by lower C inputs in sugarcane crop, relative to pasture, resulting from pre-harvest burning, a practice which was adopted in more than 70 % of the run-time simulated. Additionally, sugarcane fields pass through a cultivation cycle after four ratoons harvest, which according to field measurements cause the emission of 3.5 Mg ha^{-1} CO_2-C (Silva-Olaya et al. 2013); in contrast, pastures remain for long periods without any soil tillage.

Conversely, the positive impact on SOC stocks due to the LUC from annual cropland to sugarcane reflects the effect of annual tillage in croplands and the importance of sugarcane root system as a source of C inputs to the soil, since 50 % of the time span simulated involved burning before harvest.

Those processes of LUC associated with sugarcane expansion are an important aspect which affects the greenhouse gas (GHG) balance of sugarcane as a bioenergy feedstock and consequently the carbon footprint of the ethanol. Previous studies have indicated that energy crop expansion may result in a carbon debt (Fargione et al. 2008; Lapola et al. 2010), caused by CO_2 emissions from slash and burn of native vegetation and/or by accelerated decomposition of SOM. In this study we also assessed the effect of different sugarcane management scenarios on the SOC restoration, in order to estimate the number of years it would take to the sugarcane production system to offset the C debt caused by the land use transition.

Long-term soil C stock prediction

Changes in the sugarcane management could positively affect the soil C dynamics and play an important role in the GHG mitigation of the sugarcane production system.

Continuous burning (50-year time span) caused depletion in the soil C since this practice reduces the C inputs and accelerates the mineralization rates. The magnitude of the losses seems to be influenced by the type of native vegetation and the soil texture. The model indicated annual C losses ranging from 0.18 to 0.19 Mg ha^{-1} in areas of sugarcane expansion classified as "priority suitability" and from 0.17 to 0.43 Mg ha^{-1} in "regular suitability" areas. Higher C depletion rates were observed in clayey soils with the densest native vegetation (Atlantic forest), where considerable reduction of C inputs due to pre-harvest burning as well as the soil perturbation in the sugarcane agroecosystem affected the soil C dynamics significantly.

As burning is replaced by the green harvesting system, the C which would have been emitted to the atmosphere as CO_2 during the burning returns to the soil in the litter, thereby avoiding the continuous C loss and contributing to the soil C maintenance over the time. When compared to the burning system, the green harvesting scenario (SC1) resulted in higher soil C stocks in all the conditions simulated (Fig. 3), in agreement with modelling studies of Vallis et al. (1996); Galdos et al. (2009b) and Bortolon et al. (2011) and field measurements of Luca et al. (2008) and Razafimbelo et al. (2006). Greater C stocks were projected in clay soils within the range of soil textures represented in the dataset. Several studies have shown the importance of clay and silt in the stabilization of the SOC (Six et al. 2002; Bricklemyer et al. 2007; Tornquist et al. 2009; Bayer et al. 2011) in organo-mineral associations and soil microaggregates which reduce accessibility of SOM to microbes (Paul 1984; Lepsch et al. 1994; Lilienfein et al. 1998).

The addition of organic amendments such as vinasse and filter cake, which were simulated under the SC2, increased the C accumulation in the green harvesting system. Mineral N fertilization can still be reduced by 30 % when those residues are applied without drastically affecting the C dynamics (SC3). The combination of mineral and organic fertilization would achieve soil C stocks surpassing the level in the previous management (pasture), irrespective of the soil texture (Fig. 3).

When simulated, those organic matter additions (omad.100) supply considerable annual amounts of C and N to the soil which contribute to the increase of soil C stocks by 0.37 Mg ha^{-1} year^{-1} and 0.34 Mg ha^{-1} year^{-1} in SC2 and SC3 respectively. These results are in the range of measured C stocks increases (0.25 to 0.5 Mg ha^{-1} year^{-1}) due to this organic amendment in sugarcane crop in Brazil (De resende et al. 2006; Zani 2015), as well as consistent with the mean C rate accumulation of 0.23 Mg ha^{-1} year^{-1} projected by Galdos et al. (2009b) in a modelling study involving Brazilian sugarcane planting. Measured field data have also shown the benefits of vinnase addition in improving physical and chemical properties of the soil (Canellas et al. 2003; Zolin et al. 2011; De Souza Barros et al. 2013).

Besides the impact on SOC restoration, reductions in N fertilization rates with the use of organic amendments, as projected in the SC3 scenario, can positively affect the GHG balance of the crop. According to Carmo et al. (2013), 1.11 % and 0.76 % of the N applied in plant cane and in ratoon cane respectively, are emitted to the atmosphere as N_2O. In this way, the N reduction projected would avoid the emission of 1.32 kg ha^{-1} N-N_2O per cycle (4 ratoons) of sugarcane planting.

According to these results, recovery of the transient C loss due to the LUC related to the expansion of the sugarcane crop is possible through the adoption of conservation management practices involving returning residues to the soil plus organic matter additions.

The number of years necessary to restore the C stock varied with the texture, native vegetation and the adopted management scenario. Considering just the SC1 the model predicted that after 24 years of sugarcane the soil C stocks lost can be totally restored in clayey and loamy soils under priority and regular suitability respectively. Sugarcane involving organic fertilization (SC2 and SC3) had reduced payback times of 17 years in clayey soils and 18 years in loamy soils.

In other soil textural classes changing the harvest system was not enough to recover the losses of C. With scenarios SC2 and SC3, clayey and heavy clayey soils under regular suitability the time span is greater because of the type of native vegetation predominant in those study areas. Recovery of the C losses in sandy soils would take a mean time of 24 years for all the suitability classes.

Since the scenarios simulated in this study involved an 11-year time span of sugarcane with pre-harvest burning, we believe that the impact of LUC in new areas of expansion can be lower if conservation practices, as proposed in the SC3 scenario, are adopted immediately after the conversion. The time span for C restoration should also be lower than calculated as those practices favor soil C accumulation.

Our estimates of time span needed to pay back the soil C debt were performed just considering the soil C dynamics. The production of sugarcane ethanol has an annual GHG equivalent offset of 9.8 Mg CO_2 ha^{-1} (Macedo et al. 2008) which should also be considered in studies of life cycle analysis of this biofuel.

Our results supported the use of the Century model as tool to study the impact of different soil managements in the SOC dynamics in sugarcane. Since future expansion has been projected to primarily affect pastures and cropland areas, delivering low C renewable fuels depends on the management practices implemented. Important advantages regarding both agronomic and industrial aspects such as N fertilization when organic amendments are performed and trash retention have also been indicated by the model.

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