

**University of São Paulo
College of Agriculture “Luiz de Queiroz”**

Soil organic carbon dynamics in sugarcane crop in south-central Brazil

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Thesis presented to obtain the degree of Doctor in
Science. Area: Soil and Plant Nutrition

**Piracicaba
2014**

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versão revisada de acordo com a resolução CoPGr 6018 de 2011

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2014

**Dados Internacionais de Catalogação na Publicação
DIVISÃO DE BIBLIOTECA - DIBD/ESALQ/USP**

Silva-Olaya, Adriana Marcela

Soil organic carbon dynamics in sugarcane crop in south-central Brazil /
Adriana Marcela Silva-Olaya. -- versão revisada de acordo com a resolução CoPGr
6018 de 2011. -- Piracicaba, 2014.
100 p: il.

Tese (Doutorado) - - Escola Superior de Agricultura "Luiz de Queiroz", 2014.

1. Mudança no uso da terra 2. Fracionamento físico do C 3. Modelo CENTURY
4. Entradas de C 5. Colheita sem queima I. Título

CDD 633.61
S586s

"Permitida a cópia total ou parcial deste documento, desde que citada a fonte -O autor"

*To my lovely parents Rosendo and Ana,
My source of motivation and inspiration.*

*To Fausto Andrés for his unfailing love, belief,
understanding and encouragement.*

“It's the possibility of having a dream come true that makes life interesting”

Paulo Coelho, Alchemist

ACKNOWLEDGMENT

To God for the wisdom and perseverance that he has bestowed upon me during this phase of my life.

To my family for their unconditional support throughout my degree. Thanks for all the sacrifices that you have made on my behalf. Your prayers for me was what sustained me thus far.

To my eternal love Fausto Andrés, who taught me that who loves knows to wait, that real friends exist and that dreams can become true. Thanks for the patience, the understanding and the motivation every day.

To my advisor Professor Dr. Carlos Clemente Cerri for encouraging my research and for allowing me to grow as a research scientist.

To the graduate program in Soil and Plant Nutrition for allowing me to be one of its PhD students.

To São Paulo Research Foundation - FAPESP for the economic support of this research (process N. 2011/07105-7) and to the Brazilian Federal Agency for Support and Evaluation of Graduate Education – CAPES and Brazilian National Council for Scientific and Technological Development - CNPq for the graduate scholarship awarded.

To Professor Dr. Keith Paustian and Stephen Willians for their advise and contribution to the modelling studies.

To Shell Global Solutions and especially to Dr. Christian Davies for the scientific support.

To Professors Carlos Eduardo Pellegrino Cerri and Brigitte Feigl for their valuable contribution during the execution of this research project.

To all the technicians from Laboratório de Biogeoquímica Ambiental at CENA-USP for the friendship and cooperation during all phases of this study.

To my dears friends whom I met along the way of my graduate studies but who occupy an important space in my heart: Leidivan, Ingrid, Arlete, Ana Maria, Nada, Farnaz and David.

To all my fellows from Laboratório de Biogeoquímica Ambiental and specially to Chico for his great collaboration.

And to all the people who directly or indirectly made this possible.

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RESUMO

Dinâmica do carbono orgânico do solo na cultura da cana-de-açúcar na região centro-sul do Brasil

A cultura da cana-de-açúcar é uma *comodity* importante para a economia no Brasil. Como a principal matéria prima para a produção de etanol, a área plantada com esta cultura tem incrementado significativamente nos últimos anos e a tendência é de continuar se expandindo para atender a demanda nacional e internacional deste biocombustível. Embora tenha sido demonstrado que a mudança de uso da terra (MUT) para cana-de-açúcar pode afetar negativamente a dinâmica do carbono (C) no solo, há pouca informação disponível acerca do impacto dessa MUT na distribuição do C nas frações da matéria orgânica do solo, e como as práticas de manejo da cana-de-açúcar podem contribuir para o acúmulo de C no solo. Nesse contexto o principal objetivo desta pesquisa foi avaliar, através da modelagem matemática, a dinâmica do carbono orgânico do solo (COS) na cultura da cana-de-açúcar em resposta a mudança de uso da terra e diferentes cenários de manejo agrícola. Fracionamento físico para separar o C associado à matéria orgânica partícula (POM) do C ligado à fração mineral do solo (<53 μm) foi realizado em amostras de solo de 34 áreas de estudo envolvendo os três principais sistemas de uso da terra afetados pela expansão da cana-de-açúcar. Adicionalmente, foram realizadas avaliações biométricas da cana-de-açúcar (cana planta e soca) que objetivaram a parametrização do modelo matemático assim como recalculando o tempo de reposição do débito de C gerado. Finalmente, o modelo CENTURY foi parametrizado e devidamente validado, para posteriormente proceder à simulação de diferentes cenários futuros de manejo da cana de açúcar: i) SC1 – Colheita de cana crua (sem queima); ii) SC2 – Colheita de cana crua e adição de adubos orgânicos (vinhaça e torta de filtro); iii) Colheita de cana crua e redução da adubação nitrogenada. Os resultados indicaram que a redução do conteúdo de C devido à conversão de vegetação nativa e pastagem para cana-de-açúcar foi causada pela perda de C tanto na fração lábil (37%) quanto na fração mais estável associada a fração mineral do solo (30%). A quantificação da biomassa aérea e radicular indicou entradas de C variando de 29,6 Mg C ha^{-1} a 30,6 Mg C ha^{-1} , os quais resultariam em uma taxa de acúmulo líquido de 0,58 a 0,6 $\text{Mg C ha}^{-1} \text{ ano}^{-1}$, que quando considerado contribui a redução do “*payback time*” do débito de C do etanol causado pela conversão de Cerrado e pastagem em 3,3 e 2 anos respectivamente. Os resultados obtidos no estudo de modelagem matemática suportaram o uso do modelo CENTURY como uma ferramenta para avaliar a influência da MUT e das práticas de manejo na dinâmica do COS. As simulações em longo prazo sugeriram que a supressão da queima na colheita incrementa o estoque de C em 0,21 $\text{Mg ha}^{-1} \text{ ano}^{-1}$. No entanto o potencial de acúmulo de C é ainda maior quando adubação orgânica é realizada, com valores entre 0,34 e 0,37 $\text{Mg ha}^{-1} \text{ ano}^{-1}$ respectivamente. A análise da dinâmica do COS em cada cenário de manejo simulado permitiu estimar o tempo médio de recuperação do C do solo perdido pela MUT em áreas de pastagens. Os resultados indicaram um período de 17 anos para condições de cultivo sob solos argilosos e 24 anos para solos arenosos (SC3) em áreas de alta aptidão para expansão. O modelo projetou um maior número de anos em solo argiloso sob áreas de pastagem com aptidão média (40 anos).

Palavras-chave: Mudança no uso da terra; Fracionamento físico do C; Modelo CENTURY; Entradas de C; Colheita sem queima

ABSTRACT

Soil organic carbon dynamics in sugarcane crop in south-central Brazil

Sugarcane cropping is an important component of the Brazil's economy. As the main feedstock used to produce ethanol, the area occupied with this crop has meaningfully increased in the last years and continues to expand in order to attend to the national and international demand of this biofuel. Despite that it has been demonstrated that land-use transition into sugarcane can negatively impact the soil carbon (C) dynamics, little is known about the effect of those land use changes (LUC) processes on the distribution of soil organic carbon (SOC) within particle-size classes, and how management practices in sugarcane can contribute to the C restoration. In this sense the main objective of this study was to evaluate through a modelling application the SOC dynamics in the sugarcane crop in response to LUC and different management scenarios. For a better understanding of LUC impact on C content in both particulate organic matter and mineral-associated fraction, we performed physical soil C fractionation in 34 study areas involving the three major land-use systems affected by sugarcane expansion. Also, biometric measurements were executed in sugarcane plant and ratoon crop in order to use those data in the model parameterization as well as to recalculate the payback time of the C debt through C conversion ratio reported in the literature. Finally, we parameterized and validate the CENTURY ecosystem model for sugarcane, pastures and annual cropland by using a data-set previously collected by the Laboratório de Biogeoquímica Ambiental (CENA-USP); then different scenarios of sugarcane management were simulated: i) SC1 – Green harvesting; ii) SC2 – Green harvesting plus organic amendments and iii) Green harvesting + low N inputs. Our results showed that the C content depletion for conversion from native vegetation and pastures to sugarcane is caused by C losses in the labile fraction (37%) as wells as in the stabilized pool associated to the mineral fraction (30%). Above and belowground biomass quantification indicated a total sugarcane carbon inputs ranging from 29.6 Mg C ha⁻¹ to 30.6 Mg C ha⁻¹. Considering a C retention rate of 13% we estimated net carbon changes of 0.58 to 0.6 Mg C ha⁻¹ year⁻¹, which contribute to reduce the payback times for sugarcane biofuel carbon debts in 3.3 and 1.2 years for Cerrado wooded and pasture conversions into sugarcane respectively. The modelling study supported the Century model as a tool to access the SOC dynamics following land-use conversion and different soil management in in sugarcane. Long-term simulations suggested that changes in the sugarcane harvest from burning to green harvesting increase the soil C stock in an average of 0.21 Mg ha⁻¹ year⁻¹; however the potential of C accumulation is still higher when organic amendments as vinasse and filter cake are add to the soil, with mean values varying between 0.34 and 0.37 Mg ha⁻¹ year⁻¹ in SC2 and SC1 respectively. By analyzing the SOC dynamic at each scenario simulated, we estimated a time span of 17 and 24 years for soil C restoration in clay and sandy soils under pastures with priority suitability (SC3). The number of years was projected to be higher in clay soils with regular suitability (40 years).

Keywords: Land use change; Physical soil C fractionation; CENTURY model; C inputs; Green harvesting

1 INTRODUCTION

Sugarcane (*Sacharum officinarum* L) is a crop originally from New Guinea that grows in all tropical and subtropical regions of the world, on both sides of the equator, up to approximately 35° N and 35° S (GOMES; LIMA, 1964).

As a plant with C4 photosynthetic cycle, and highly efficient in turning solar radiation into biomass, sugarcane is cultivated in more than 70 countries occupying an area of 26 Mha with a total production of 1832 million tons (FAO, 2014).

The aerial part of the plant is composed of multiple stems or culms consisting of a series of nodes separated by internodes where the sucrose is accumulated, and the tops and leaves which form the trash of the sugarcane. All these components result in about 35 Mg ha⁻¹ of dry matter (NOGUEIRA et al., 2008).

In Brazil the sugarcane has been cropped since colonial period when the plants were brought from Madeira Island in 1515 (CHEAVEGATTI-GIANOTTO et al., 2011). Currently, after a long evolutionary process, Brazil is the world's largest sugarcane producer, with approximately 10 Mha cultivated accounting for 39% of the world production (FAO, 2014).

With a variable cycle, which depends of local climatic conditions, variety and cultural practices, sugarcane is replanted in Brazil every five to six years when the yield decline reaches an economically unfeasible level (MATSUOKA; GARCIA; CALHEIROS, 1999). Generally, the first harvest is made 12 or 18 months after planting. The following ratoon cane harvests are made once in a year until field renewal (MACEDO; SEABRA; SILVA, 2008). Two harvesting system are implemented in Brazilian sugarcane production: i) Semi-mechanized harvest, in which the cane is harvested manually after the burning of the residues and loaded onto trucks mechanically; and ii) Green harvesting where the cane is harvested by machines without prior burning of the trash (CHEAVEGATTI-GIANOTTO et al., 2011; GALDOS et al., 2010).

Due to its vigorous grown, photosynthetic efficiency and a production system that often includes the use of crop residues to generate power or processing mills, sugarcane is the most attractive feedstock for bioethanol production (GALDOS et al., 2010). Currently, half of the sugarcane production in Brazil is used for ethanol fabrication (CONAB, 2013) and because of this use the sugarcane industry has introduced considerable improvements to the sugarcane chain. Structural changes in the processing and agricultural phase have resulted in a substantial increase of the national production reaching an important value of 561 million tons

in the harvest season 2011/2012, compared with about 70 million tons processed in 1974/1975 (BRASIL, 2007; COMPANHIA NACIONAL DE ABASTECIMENTO - CONAB, 2013).

Production and use of sugarcane-based fuel ethanol in Brazil began in 1975 with the launch of the Alcohol Program (Pro-Álcool), which resulted in the development of ethanol-fueled vehicles and flex-fuel vehicles and made sugarcane an important source of renewable energy, accounting for more than 56 percent of gasoline use (VALDES, 2011) and contributing to the diminishing of greenhouse gases (GHG) emissions.

The rapid growth of the sugarcane and ethanol industry has been accompanied by the increase in the area occupied by this crop. In the last five years almost 3 million hectares of sugarcane were added to the production system (CONAB, 2008, 2013) reaching a total planting area that represents 14% of total area harvested in the country (INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA - IBGE, 2014). According to the most recent land use data for Brazil more than 90% of that expansion has been concentrated in the south-central region of the country and the land use dynamics indicates the replacement of pastures (71%) and annual cropland areas (13%). The conversion of natural vegetation into sugarcane has occurred in the past, but represents less than 1% of the expansion in this region (CONAB, 2010, 2013).

Growth has not stopped yet and the expansion processes could be even more intense in response to the national and international demand of bioethanol. Future projections of the sugarcane sector aim to increase the ethanol production to ~60 billion of liters in the next 5 years. To achieve this goal the planting area with sugarcane should reach the significant level of 19 Mha (BRASIL, 2009; CERRI et al., 2010; GOLDEMBERG et al., 2014) following the trend of land use change (LUC) observed in the past (NASSAR et al., 2008).

Despite that such expansion would favor ethanol production, there are issues regarding the impact of LUC on the greenhouse gases (GHG) balance of the sugarcane crop. The burning of native vegetation, decomposition and oxidation of the soil organic matter (SOM) caused by the LUC can result in GHG emission to the atmosphere (CERRI et al., 2007; FEARNSIDE et al., 2009), leading a decrease in soil carbon stocks (LAL; KIMBLE, 1997; SIX et al., 2002) and consequently affecting the overall sustainability of the ethanol.

Recent studies have indicated that energetic crops expansion into native and agricultural land uses can result in a transient “carbon debt” (FARGIONE et al., 2008; GIBBS et al., 2008; LAPOLA et al., 2010; MELLO et al., 2014). Estimates performed in Brazil

demonstrated that the conversion from native vegetation and pastures to sugarcane results in a C debt of 77 and 21 Mg CO₂ ha⁻¹ respectively, with payback times ranging from 17 years in native vegetation and from 5-6 years in pastures (MELLO et al., 2014). Conversely, when sugarcane replaced annual cropland the soil C stocks increased by 17% in the 0-30 cm soil depth (MELLO et al., 2014).

In this context, the main goal of this research was to model the soil organic C dynamic in sugarcane crop as affected by different LUC processes and soil management. A soil data-set involving the three major LUC scenarios collected by the researches of “Laboratório de Biogeoquímica Ambiental” from CENA-USP and published recently by Mello et al. (2014) was used for this purpose.

Firstly, physical soil C fractionation was performed at 34 sites, i.e. from 17 comparison pairs of land-use transition to sugarcane, including native vegetation, pastures and annual cropland, in order to study the impact of LUC on the C content in particle-size fractions, based on the premise that SOM associated with particles of different size and therefore also of different mineralogical composition, differ in structure and function (CHRISTENSEN, 1992) and can be differently affected by the LUC (Chapter 2 - Changes in soil organic carbon fractions in response to sugarcane cultivation in south-central Brazil).

Subsequently, field measurements of sugarcane biomass regarding aboveground as well as belowground productivity were executed in three experimental areas located in São Paulo state. Estimates of shoot:root ratio and net annual carbon inputs to the soil for sugarcane for different ratoon stages were performed and payback time recalculated considering that information (Chapter 3 - Quantifying above and belowground biomass carbon inputs for sugarcane biofuel production in Brazil).

Finally, the CENTURY model was parameterized upon reviewing data obtained in literature and using the results from above and belowground measurements at sugarcane. After confirming the accuracy of the model different scenarios of management were simulated (Chapter 4 - Modelling SOC variation due to land use change and management practices in sugarcane crop in south-central Brazil).

The results generated during this research are an important tool for the sugarcane sector. Prediction of future agroecosystems states in response to of different management practices are valued aspects of model application which can drive decision makers and planners to develop sustainable soil management systems insuring proper GHG mitigation measures.

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2 CHANGES IN SOIL ORGANIC CARBON FRACTIONS IN RESPONSE TO SUGARCANE CULTIVATION IN SOUTH-CENTRAL BRAZIL

Abstract

Sugarcane planting area in Brazil has considerably increased during recent years by occupying areas used for pasture and grain crops production. Land use change (LUC) processes related to sugarcane expansion can affect the soil organic carbon (SOC) stocks and the quality of the soil organic matter. Preliminary studies have shown that the land-use transition into sugarcane lead a decrease in the SOC, however no studies have accessed the impact of LUC on the SOC distribution within soil particle-size classes. We investigated the modifications on total SOC, particulate organic carbon (POM) and mineral-associated C (MOM) in response to conversion from native vegetation (NV), pastures and annual cropland (AC) to sugarcane crop (SCN). Soil samples were collected at 34 field-sites to 0.2 m depth and POM fraction separated through 53-mm sieve after soil dispersion. Our results indicated that LUC affects both the labile as well as the more stable SOM fraction, with a mean C content decreasing of 40% and 30% in POM and MOM respectively, following the transition from NV to SCN. The replacement of pastures caused C depletion by 33% at POM and 30% at MOM; meanwhile C accumulation at MOM (5%) was detected for the conversion from AC to SCN. The impact of LUC on POM for AC-SCN transition could not be totally clarified, however the result could be an indication that the POM response to LUC varies as function of previous management in AC.

Keywords: C fractionation; Particulate organic matter; Mineral-associated C; Land use change; C depletion

2.1 Introduction

Sugarcane (*Saccharum officinarum* L) is a perennial grass originating from New Guinea that has been cropped in Brazil since the colonial period, reaching a harvested area of 9.7 Mha which accounts for 40% of worldwide production (FAOSTAT, 2014).

Since sugar from sugarcane is the main feedstock used to produce ethanol in Brazil, the planted area with this energetic crop has meaningfully grown in the last decade, and the trend is to continue expanding for the next years in order to achieve the national goals of production (CONAB, 2013; BRASIL, 2009; CERRI et al., 2010; GOLDEMBERG et al., 2014).

As the soil is an important natural reservoir of carbon (C), land use changes (LUC) during the transition to sugarcane production can lead to a decrease in soil carbon stocks (LAL; KIMBLE, 1997; SIX et al., 2002). Land use and land changes are widely recognized as key drivers of global C dynamics (SCHIMEL, 1995; HOUGHTON, HACKLER; LAWRENCE,

1999). Soil organic matter (SOM) has a very complex and heterogeneous composition and it is generally mixed or associated with the mineral soil constituents to form soil aggregates (DEL GALDO et al., 2003).

A recent study performed in Brazil demonstrated that the greenhouse gases (GHG) emissions due to LUC for conversions from native vegetation and pastures to sugarcane could result in net transitional soil C debt with payback times ranging from 17 years in native vegetation and 5-6 years in pastures. Conversely, when sugarcane replaced annual cropland the soil C stocks increased by 17 % in the 0-30 cm depth layer (MELLO et al., 2014).

In addition to the C quantity, land use practices affect the soil C quality varying the distribution between particulate organic matter and SOM associated to the mineral fraction (CAMBARDELLA; ELLIOTT, 1992; CHRISTENSEN, 2001). Christensen (2001) proposes that the main effects of land use management can be observed by changes in the distribution of soil organic carbon (SOC) within particle-size classes.

Several studies have shown the influence of soil tillage system on the C pools, suggesting that particulate organic matter can be used as an early indicator of changes in C dynamics (CAMBARDELLA; ELLIOTT, 1992; SIX; ELLIOTT; PAUSTIAN, 1999; BAYER et al., 2002; FREIXO et al., 2002). However few studies have been carried out to determine the impact of LUC on particle-size fractions, and no studies have been performed involving the land-use transition into sugarcane.

The correct evaluation of soil C changes and SOM dynamics is the one which functionally distinguishes among different SOM fractions. The development of management systems for sustained production requires a better understanding of the impact of land-use and LUC in the SOM pools.

In this context this study aimed to investigate the modifications on total soil organic C and C content of the particle-size fractions, as results of LUC due to sugarcane planting in south-central Brazil. We used the physical fractionation method, based on the premise that SOM associated with particles of different size and therefore also of different mineralogical composition differ in structure and function (CHRISTENSEN, 1992).

2.2 Materials and methods

2.2.1 Study area

The study area involved seven counties distributed throughout the south-central region of Brazil, covering the states of Minas Gerais, São Paulo, Goiás and Mato Grosso do Sul. Comparative soil samples were collected from sugarcane fields and native vegetation, pastures and annual crops. The selection of the study areas considered historical land use information and existence of reference areas (pasture, annual cropping or native vegetation) with similar geomorphic characteristics (topography, soil type etc.) as the sugarcane sites. Consequently, 34 study sites forming 17 comparison pairs (CP) were selected for soil sampling: 13 CP involving land use transition from pasture to sugarcane, 2 CP involving transition from native vegetation (Cerrado) to sugarcane and 2 CP where sugarcane replaced annual crops (soybean /corn).

Soil texture of the study areas ranged from sandy to heavy clayey, with a mean time span of 13 years for sugarcane cultivation and an average of sugarcane green harvesting management of 3 years (Appendix A).

2.2.2 Soil sampling and C determination

In each evaluated site, three pits were opened and soil samples were taken from the layers of 0-10 cm and 10-20 cm depth, totalizing 6 soil samples per site and 204 for the study area. Soil samples were sieved (2 mm), ground and sieved at 150 μ m for carbon determination by dry combustion on a LECO[®] CN elemental analyzer (furnace at 1350° C in pure oxygen).

Soil C fractions were determined according to the method described by Cambardella and Elliott (1992) and adjusted by Feller and Beare, (1997) and Christensen, (1997). Briefly, 20 g of 2-mm sieved soil was mixed with 80 mL of hexametaphosphate solution (0.5%), refrigerated and subsequently sonicated for 15 minutes with a maximum power output of 500 W. The dispersed soil was sieved through a 53- μ m sieve and the sand-sized organic material (POM) retained on the sieve was thoroughly rinsed, transferred to aluminum pans, oven-dried (60°C), and weighed. The dried samples were ground and the total carbon content in the fraction was determined by dry combustion on a LECO[®] CN elemental analyzer. Mineral-associated C (MOM) was estimated by difference between total C (TOC) and POM C.

2.2.3 Statistical analyses

The study was arranged in a completely randomized design comprising four land use systems (LUS) with three pseudo replications. Data was checked for normality using the Shapiro test and for homoscedasticity by Bartlett test. Analysis of variance with the F-test was performed and differences detected were compared using the Tukey tests at a significance level set at $P = 0.05$.

The comparison of the relative portion of the fractions (POM and MOM) was performed using the Student t test. Changes in the TOC and the C content in each fraction were estimated considering the means between CP, hence descriptive analysis is presented for those results since only two CP were studied for native vegetation and annual crops situations.

2.3 Results

2.3.1 Total soil organic C and relative fractions of POM and MOM

The TOC content was quantified for all the LUS involving both layers: 0-10 and 10-20 cm depth (Fig 1A). The mean comparison test performed, which included all the sugarcane sites without considering the previous management, indicated TOC higher in native vegetation than in the other LUS in both depths, with more contrasting differences in the top layer. The TOC in pastures was higher than quantified in sugarcane only in the 0-10 cm layer. No significant differences ($P < 0.05$) were detected between sugarcane and annual cropping.

Carbon content in POM and MOM fractions was influenced by management at all sites and differences varied across depth. In the top layer (0-10 cm depth) the C in POM was more variable than in 10 - 20 cm layer, where no differences were estimated among the planted areas. Opposite pattern was found for the C content in the MOM fraction (Fig 1A).

A trend of C declining with depth was observed in all the LUS. The TOC was 1.3 times lower in the deeper layer than in the top with changes more contrasting at MOM than in POM fraction.

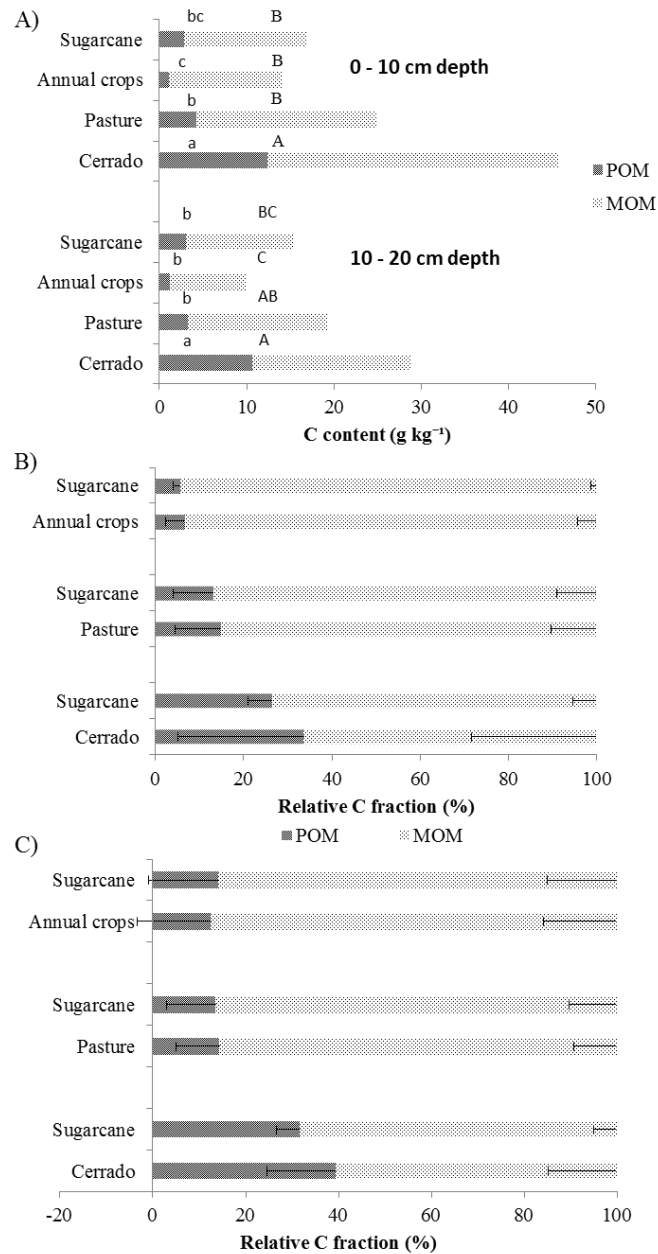


Figure 1 - Total soil organic C (g kg⁻¹) in each land use system for the 0 -10 cm and 10 – 20 cm depth (A) and its relative portion (%) of particulate organic C (POM) and mineral-associated C fraction (MOM) for each conversion type involving sugarcane planting in 0 -10 cm depth (B) and 10 – 20 cm depth (C)

* Means followed by the same capital letter within MOM and same lowercase letter within POM fraction in each layer are not significantly different according to Tukey's test at the 5% level

The mean relative amount (%) of POM and MOM as a portion of total soil C was estimated for the sugarcane sites and compared with the LUS used as reference (Fig 1B and 1C). According to the statistical analysis the relative portion of both soil organic C fractions was not different between sugarcane and the areas selected as reference of previous management for the two soil depth studied.

The proportion of POM in the condition accessed was affected by the soil clay and silt content. Relationships between POM relative fraction and silt plus clay content occurred in both layers, with higher coefficient of correlation in the 10 – 20 cm depth than in the top layer (Fig 2).

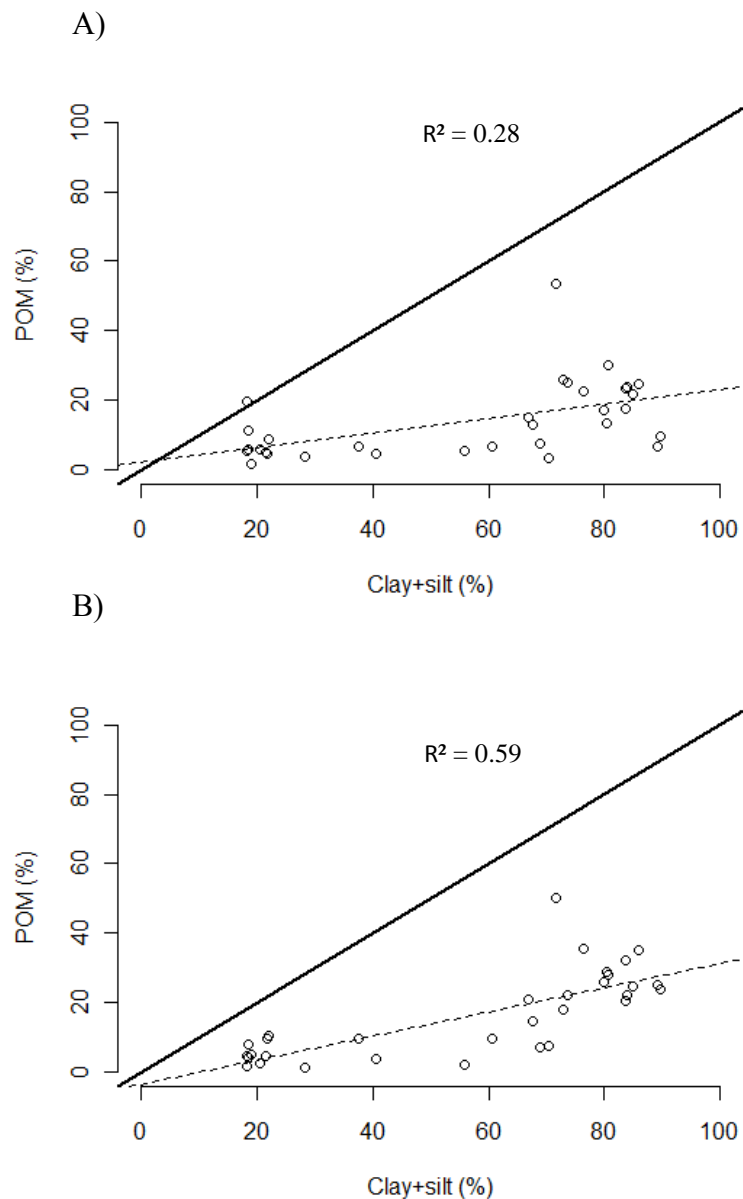


Figure 2 – Lineal regression between particulate organic C (POM) and clay + silt content (%) for the study areas in 0 -10 cm depth (A) and 10 – 20 cm depth (B).

2.3.2 Relative changes in soil C fractions

Carbon variation for each fraction due to the planting of sugarcane was quantified through the difference between the mean C content found in the sugarcane areas and their references. Subsequently the relative change in each C fraction was estimated (Table 1).

Greater C losses were found for the conversion from native vegetation to sugarcane crop. The LUC affected the labile organic carbon (POM) as well as the more stabilized C fraction (MOM). The impact of those processes was higher in the superficial layer than in the 10 – 20 cm layer.

In contrast, sugarcane planting over areas used for annual cropping production seems to increase the SOC, favoring the C accumulation in the mineral-associated fraction.

Table 1 - Relative changes (%) in total C content (COT), particulate organic C (POM) and mineral associated C (MOM) due to the sugarcane planting in south-central Brazil

Reference	COT	POM	MOM
0 - 10 cm depth			
Cerrado	-48.6	-50.82	-47.89
Pasture	-34.5	-37.11	-33.97
Annual crops	3.25	-23.13	5.53
10 - 20 cm depth			
Cerrado	-17.8	-29.15	-11.22
Pasture	-24	-20.18	-24.80
Annual crops	5.8	7.90	5.37

2.4 Discussion

Soil organic carbon content reflects the long-term balance between additions and losses of organic carbon to the ecosystem. In this study we compared the TOC content among the different LUS accessed without considering the previous management of the sugarcane areas. Under this approach, higher C contents were found at native vegetation in both soil depth studied, in agreement with results reported in tropical soils. All studies that focused on the effects of land conversion from forest to cultivated land concluded 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 50% in the first years of cultivation due to

several processes, including microbial decomposition and erosion (MIELNICZUK; SANTOS; CAMARGO, 1999).

When compared with pastures we estimated that TOC under this land use system was 45% and 32% lower than native vegetation in 0 – 10 cm and 10 – 20 cm depth, respectively. Carvalho et al. (2010) studying different pastures areas in the Brazilian Cerrado region found C content varying as a function of the pastures management. Pasture lands can lead either to a positive or negative impact on the overall soil C. In this study lower C content can be attributed to degradation process caused by the soil management. More than 70% of the total areas under cultivated pastures in Brazilian Cerrado region show some degree of degradation (MARTHA JUNIOR; VILELA, 2002; BATLLE-BAYER; BATJES; BINDRABAN, 2010) due to increasing stocking rates without maintenance fertilization, which results in a rapid decline of nutrients in the soil (NAIR et al., 2011).

Even though no significant differences ($P < 0.05$) were found in the C content of POM and MOM fractions among the planted areas, a trend of decreasing MOM (g kg^{-1}) from pasture to sugarcane areas (Fig 1a) and in both fractions to annual crops sites was observed, pointing out the contrasting impact of the land use in SOC dynamic. Soil tillage has been indicated as a highly disturbing management practice (SILVA-OLAYA et al., 2013) which alters aggregate dynamics by enhancing the turnover time of SOM thus decreasing the formation of the more stabilized C fractions, such as POM C and mineral-associated C (SIX; ELLIOTT; PAUSTIAN, 1999).

Regarding the percentage of C presented for different fractions, we found that POM fraction varied from 6 % to 34 % in the LUS evidencing the differences in C inputs into the soil and the role of the historical use in the C dynamics, since the relative fractions in sugarcane crop followed the same pattern observed in the reference sites. Excepting for the annual crops areas, where less than 10% of POM was found, the values observed were within the range of values indicated by Feller and Beare (1997). C-turnover rates for the particulate organic matter associated with the sand-size fraction are higher, hence it is more depleted by annual cultivation than clay-bound organic matter (CHENU; PLANTE, 2006).

Despite the land use system affected the soil C content of all fractions, the sugarcane planting did not affect their proportional weight distribution when compared to the LUS reference (Fig 1B and 1C). The mean relative portion of POM and MOM does not vary significantly between sugarcane and its references in both layers, suggesting C losses in the

labile fraction as well as in the stabilized pool, hypotheses corroborated later when estimated the relative change of each fraction as function of its reference (Table 1).

Mello et al. (2014) accessing the effects of LUC due to the sugarcane planting in south-central Brazil on soil C stocks demonstrated soil C decrease following LUC from native vegetation and pastures, and increase where cropland is converted to sugarcane. In our study, using some of the areas sampled by Mello et al. (2014) we estimated that the conversion from native vegetation to sugarcane crop affects both SOM pools. Particulate organic matter was the most sensitive fraction to LUC and declined by an average of 40% followed by the silt and clay sized fractions which had 30% less C in the surface soil horizon (0 – 20 cm depth) after the conversion.

The same pattern was observed when sugarcane replaced pastures. Mean C losses of 33% and 30% in POM and MOM, respectively, were quantified for the same soil depth.

By analyzing each layer we found that the impact of LUC of SOC variation is greater in the top layer for both types of land use conversion, where wake relationship between POM and clay plus silt content was observed, evidencing that likely much of the POM found in this depth correspond to free particulate organic matter or unprotected SOM, which is relatively easily decomposable and are greatly depleted upon cultivation (CAMBARDELLA; ELLIOTT, 1992; SIX; ELLIOTT; PAUSTIAN, 1999). At the 10 -20 cm depth the correlation between soil texture and relative fraction of POM suggests a protection of the labile C from decomposition in the inter-aggregates (occluded POM), which can influence in the rate of C losses with soil perturbation.

Even though SOC associated with mineral soil (MOM) is considered the more stable and recalcitrant fraction of SOM (WIESENBERG; DORODNIKOV; KUZYAKOV, 2010) these results imply that a significant proportion of the SOC at that pool is relatively labile, as suggested by Feller and Beier (1997) and hence it is negatively affected by the LUC.

Upon reviewing data obtained in literature Von Lutzow et al. (2007) estimated that the generally higher allocation of SOC in smaller particles is not always congruent with a longer turnover time. In the sand fraction, ^{13}C turnover times ranged from 0.5 to 374 years, in the silt fraction from 115 to 676 years and in the clay fractions from 76 to 190 years. The same trend was observed when used ^{14}C as indicator of mean residence time (MRT). Additionally, the authors found that the MRT and turnover time of fine clay is lower in than in the coarser clay fraction.

García-Oliva et al. (1994) reported that the C silt-associated fraction was subject to a lower loss rate than the clay-associated C fraction in a tropical deciduous forest after conversion to pasture. Similar results were found by Covalada et al. (2011) comparing conserved and degraded forest soils. The clay-fraction is more enriched in new SOM because of microbial activity which decomposed faster than the silt-sized aggregate fraction (GREGORICH; VORONEY; KACHANOSKI, 1991).

Since we estimated the C associated with the mineral fraction as the difference between TOC and POM, we believe that those differences between clay and silt association to SOM could explain the susceptibility of MOM to LUC in our study. Moreover, sugarcane crop maintains lower amounts of SOM when compared to pastures and native vegetation. Pre-harvest burning performed in this crop affects the potential mineralizable C of the SOM labile pool, soil microbial biomass and physical soil properties influencing the soil aggregation which is one of the main SOM stabilization mechanisms (PRIETO-FERNÁNDEZ; ACEA; CARBALLAS, 1998; CEDDIA et al., 1999; SIX et al., 2002; DE SOUZA et al., 2005). Also, sugarcane fields pass through a cultivation cycle every 5 to 6 years which causes the emission of $3.5 \text{ Mg ha}^{-1} \text{ C-CO}_2$ (SILVA-OLAYA et al., 2013); meanwhile either pastures or native vegetation remain for long periods without any soil perturbation.

In contrast to both conversions mentioned above, the LUC from annual cropland to sugarcane increased the TOC. According to Mello et al. (2014) the C stocks in sugarcane areas were 17% higher, leading to an accumulation of $36 \text{ Mg CO}_2 \text{ ha}^{-1}$ in the 0 – 30 cm of soil depth after 20 years of time span. In this study, using two of the CP reported by Mello et al. (2014) we estimated that 5% of that C increases occurred in the MOM fraction. Mean C depletion of 23% in POM fraction was observed at the 0 – 10 cm of soil depth and C accumulation at the deeper layer; however because of the high standard deviation of this parameter in both areas (sugarcane and annual crops) the POM dynamics cannot be conclusive. The two cropland areas had different management history and also different clay + silt content, variable that can influence the relative portion of the labile pool as indicated by the regressions performed for the 10 – 20 cm of soil depth.

The combination of crop rotation and no-till at one of the reference sites resulted in higher C content at POM at the top layer which is depleted because of the conversion to sugarcane. In the 10 – 20 cm of soil depth the high clay + silt content of the same area seems to offer some degree of physical protection to labile fraction thus this is not strongly affected by the LUC. Conversely, management as well as soil attributes at the other reference site resulted in

the opposite dynamic, thus C content in POM increased with the sugarcane planting in both layers. Even though the results of this pool cannot be conclusive, those could be an indication that the POM response to LUC varies as function of previous management in annual cropland, however a larger sample size of annual cropland to sugarcane conversion would be necessary to better evaluate soil C changes at the labile pool and to confirm that hypothesis.

Sugarcane expansion in south-central Brazil is an important process that can affect the greenhouse gases (GHG) balance of this energy crop and consequently the overall sustainability of the biofuel production. In this sense, our results provide essential knowledge about the SOC dynamic due to those LUC processes. With future expansion projected to involve mainly pastures and cropland areas it is important to develop management systems in sugarcane production that allow for the restoration of the stable C fraction (MOM) which has been considerably depleted because of the conversion from pastures, contributing to long-term soil C sequestration.

2.5 Conclusions

The proportion of particulate organic matter at 10 – 20 cm depth is affected by the clay+silt content. Land-use conversion from native vegetation and pastures to sugarcane modifies the distribution of C within soil particle-size classes. Important C depletion in the stable fraction of SOM as well as in the labile fraction is caused by those kinds of transitions. In contrast, C accumulation in MOM is favored by the replacement of cropland areas by sugarcane.

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3 QUANTIFYING ABOVE AND BELOWGROUND BIOMASS CARBON INPUTS FOR SUGARCANE BIOFUEL PRODUCTION IN BRAZIL

Abstract

Brazilian ethanol production is based primarily on sugar from sugarcane; and this biofuel has both an energy and GHG balance that makes it one of the most sustainable biofuels currently produced at commercial scales. Due to the increasing demand for sugar and ethanol, sugarcane production is expanding into other land uses, which can have a significant impact on soil organic matter dynamics. The overall impact of land use change into bioenergy crops can impact both existing soil carbon stocks, and also subsequent input of new carbon from above and belowground biomass, the net balance of which determines the overall carbon intensity. Here we present the above and belowground dry biomass production, shoot to root ratio (S:R) as well as the net annual carbon inputs to the soil for sugarcane for different ratoon stages. The selected areas were: i) recently planted sugarcane area (PC), ii) first year ratoon cane (RC1) and iii) four year ratoon cane (RC4). The sugarcane S:R ratios ranged from 6.6 in PC to 3.4 in RC4, and total sugarcane carbon inputs from 29.6 Mg C ha⁻¹ to 30.6 Mg C ha⁻¹. The net carbon change due to sugarcane inputs was 2.9 to 3.0 Mg C ha⁻¹ for each sugarcane cycle of four ratoons. With the revised sugarcane carbon inputs, the payback times for sugarcane biofuel carbon debts are less than previously reported in 3.3, 2 and 1.2 years for Cerrado wooded, Cerrado grassland and pasture conversions into sugarcane respectively.

Keywords: Land use change; Soil carbon; Ethanol; Roots; Shoots; *Saccharum spp.*

3.1 Introduction

Brazil is the second largest producer of ethanol in the world, accounting for 32% of the market share (BAIER et al., 2009), production is based primarily on sugar from sugarcane; with an energy and greenhouse gas (GHG) balance that makes it one of the most sustainable biofuels currently produced at commercial scales (WALTER et al., 2008).

Sugarcane is a C4 plant highly efficient in turning solar radiation into biomass, 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; SEABRA; SILVA, 2008).

Over the past 20 years there have been significant improvements introduced to the production of sugarcane ethanol, primarily associated with the use of bagasse (Residue obtained after sugarcane is milled for juice extraction) for production of electricity, and recently the use of sugarcane trash (residual biomass following mechanised harvest) to increase this renewable energy production capacity (PIPPO; LUENGO, 2013). Traditionally,

the tops and leaves are burned before the harvest in order to facilitate this operation. However, legal restrictions regarding the sugarcane pre-harvest burning have been implemented recently in Brazil. According to National Supply Company (CONAB) 64% of the total harvested area in 2011-2012 crop season involved mechanical harvest without burning, which large quantities of residues remain on the soil surface providing several potential benefits to the system (HARTEMINK, 2008).

Even though those improvements in the sustainability and efficiency of sugarcane production and the ethanol manufacturing process, other agricultural practices in the field can have a significant impact on the GHG balance through improved soil organic matter (SOM) dynamics and subsequently overall sustainability of a biofuel. The effects of land use change (LUC) during transition to sugarcane production and management can lead to decreases in carbon stocks (LAL; KIMBLE, 1997; SIX et al., 2002), and increases in atmospheric GHG emissions. It has been shown that increases in SOM within agroecosystems are positively correlated with the amount of C inputs ((BLAIR et al., 1998; THORBURN et al., 1999; ROBERTSON; THORBURN, 2007; GALDOS; CERRI; CERRI, 2009), and conversely decrease rapidly following land use change or reduction in biomass carbon inputs.

Despite the ongoing reduction in GHG emission associated with replacing fossil fuels with biofuels, the effects of LUC on soil carbon for biofuel crops can result in a transient “carbon debt”, with the expansion of energy crops into native and agricultural land uses (FARGIONE et al., 2008). In Brazil the GHG emissions due to LUC for conversions from native vegetation to sugarcane, based on limited data for both stock changes and sugarcane carbon inputs, could result in net transitional soil carbon losses with payback times from 17 to 100 years (FARGIONE et al., 2008; GIBBS et al., 2008).

However, the majority of Brazilian sugarcane expansion is occurring in non-native, arable, and pasture land uses (CONAB, 2012), and this could result in reduced payback times due to increases in soil organic carbon inputs under sugarcane cultivation (GIBBS et al., 2008). This non-native LUC for sugarcane could result in a carbon credit, not accounting for any potential indirect effects associated with subsequent agricultural expansion (iLUC) into native land uses (e.g. cerrado grassland) (LAPOLA et al., 2010). The potential for a biofuel “carbon credit” from measured sugarcane carbon inputs could therefore be significant, and offset potential soil carbon losses following the initial conversion.

Improved characterization, prediction and management of soil carbon dynamics under sugarcane are necessary to quantify carbon inputs to soil (BOLINDER et al., 2007). The

ability to predict the soil carbon balance depends on reliable estimates of net above and belowground biomass, and the proportion that is returned to the soil. For sugarcane this information has been lacking due to the difficulties in estimating inputs (primarily from the belowground fraction). The carbon inputs from the root biomass at harvest are usually calculated using estimates of shoot to root ratios (S:R) at the time of peak standing crop (BOLINDER; ANGERS; DUBUC, 1997). The root system represents a significant C input to the soil (BALLCOELHO et al., 1992). However little is known about the real contribution of this plant compartment in soil C cycling. In this study production of aboveground and belowground dry biomass from sugarcane were quantified, to determine the S:R ratio as well as the net and gross annual carbon inputs to the soil from sugarcane production in Sao Paulo state, the most important sugarcane producer in Brazil, to improve current Life Cycle Analyses for sugarcane ethanol. We hypothesized that the implementation of mechanical harvest at sugarcane crop would contribute to the reduction of the payback time of carbon credit caused by the sugarcane expansion over other land use systems in Brazil.

3.2 Materials and Methods

3.2.2 Study Area

The study area was located near to Piracicaba, in northeastern São Paulo State, Brazil. The region is classified according to Köppen Climate Classification (1936), as Aw: tropical with a wet summer and a dry winter. The precipitation of the driest month (August) is less than 30 mm, the average temperature of the hottest month (February) is 31°C and the average temperature of the coldest month (July) is 10°C. Mean temperature and precipitation in the study year were 21.4°C and 1,271 mm, respectively. Three experimental areas under similar soil, climate, topography and management, but at different periods of establishment since planting (chronosequence approach) were selected to perform this study. The sites consisted of a recently planted sugarcane area (PC), a first year ratoon cane (RC1) and a four year ratoon cane (RC4). All three study areas were planted with the same sugarcane variety RB86-7515 and harvested using the same mechanical harvesting system (i.e. without burning).

The soil under the three experimental areas was classified as Typic Quartzipsamments (Estados Unidos. Departamento de Agricultura, 1999), with 853 g Kg⁻¹ sand, 75 g Kg⁻¹ clay in PC; 793 g Kg⁻¹ sand, 129 g Kg⁻¹ clay in RC1 and 885 g Kg⁻¹ sand, 45 g Kg⁻¹ clay in RC4.

The planting system adopted in PC and RC1 areas consisted of double furrow planting, with two crop rows 0.9 m apart, separated by 1.5 m (and a furrow) from the next paired rows. In RC4 the planting system followed a homogeneous distribution with row spacing of 1.4 m.

3.2.3 Above and belowground biomass

Dry biomass production above and belowground was assessed using a randomized design with three replicates in each experimental area. Plot dimensions were 2.4 m x 3 m (7.2 m²) in PC and RC1 and 2.8 m x 3 m (8.4 m²) in RC4. All plots consisted of 2 rows with a row length of 3 m.

To quantify aboveground biomass all the vegetation inside each sampling plot was collected manually in October 2011 before the harvest operation, then separated into green leaf blades, dry leaf blades, roll leaves (leaf sheaths) and stalks (culms). Each of these fractions was weighed and one sub-sample (approximately 10% of the total fraction dry weight) from each dried at 60°C until reaching a constant dry weight. Each aboveground sub-sample was milled and its C content quantified by dry combustion in a LECO CN-2000 (NELSON; SOMMERS, 1996).

Belowground root biomass was evaluated using monoliths from Voronoi polygons, which is the space defined by the half distances between the sampled plant and its neighbors (SAINT-ANDRE et al., 2005), typically spaced 0.3 m apart. Thus one plant from each plot was randomly selected and the Voronoi polygon sampled according to the row spacing specific to each experimental area. One trench of 1.0 m (depth) × 0.3 m (length) × 0.45 m (width) was dug in the plots corresponding to PC and RC1 and of 1.0 m (depth) × 0.3 m (length) × 0.70 m (width) in the RC4 area. In each trench all the soil within half of the Voronoi (Fig. 1) polygon was collected every 20 cm down to 1 m.

Once the monoliths were removed, they were weighed and gently washed in a sieve kit composed of a series of reducing mesh sizes (5 to 2 to 1 mm) to separate roots from soil particles. Root samples were oven-dried at 60°C until a constant weight was obtained. The root mass was then manually separated from the decomposed litter prior to grinding and weighing for total C analysis using dry combustion in a LECO CN-2000.

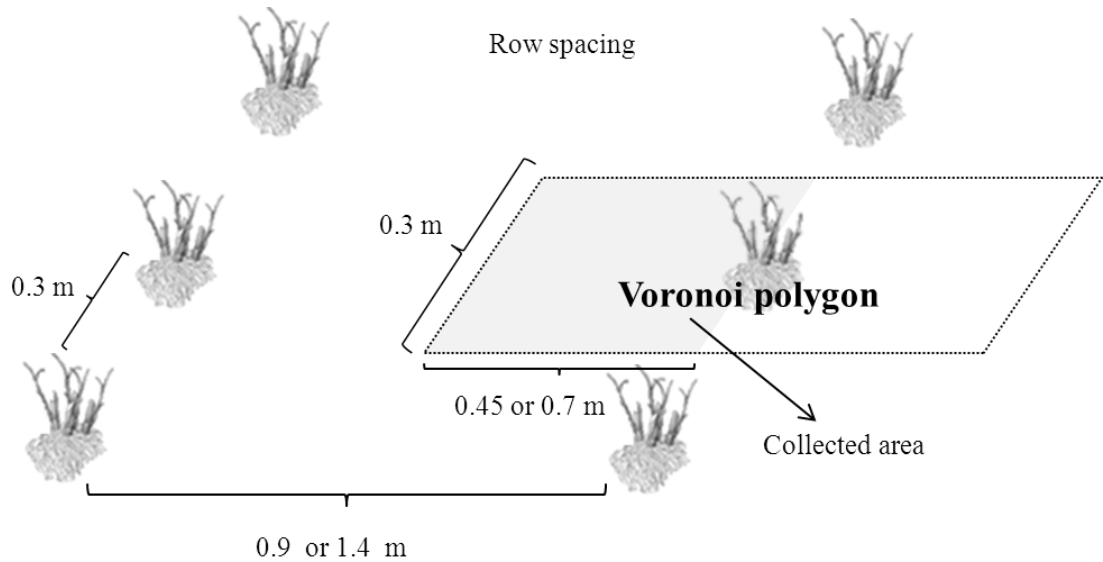


Figure 1 – Protocol for root extraction adapted from Sain-André et al. (2005)

3.2.4 Shoot-to-root ratio estimation

The shoot-to-root ratio (S:R) is commonly used to calculate C inputs from the root biomass left in the soil after harvest (BOLINDER et al., 1999). The S:R ratios were calculated using the data from total dry biomass of aboveground and total root dry biomass quantified until 1 m depth.

3.2.5 Annual Carbon Inputs to Soil

Estimates of above and belowground annual soil C inputs from sugarcane were calculated from the dry biomass weight and carbon content in each fraction and soil rooting depth sampled. The aboveground annual C inputs can be estimated as the sum of total carbon in green leaves (C_{gl}), dry leaves (C_{dl}), and leaf roll (C_{lr}), since the stalk is the product of commercial interest and not a carbon input to the soil. However in the mechanized harvest system adopted in sugarcane, not all fractions of stalk are harvested (some fractions remain on the soil after harvest), here termed harvest loss (hl), as well as not all the leaves and leaf roll remain in the field after harvest, some of this is removed with the stalk, we term these losses vegetal impurities (vi). The proportion of hl and vi varies as result of phenological characteristics, culture management and harvest system. In the experimental areas hl accounted 2.8% of stalk compartment and vi accounted 5.87% of the sum of leaf roll and

leaves, for the year studied. Thus, aboveground annual C inputs (C_i) were calculated using the following equation:

$$C_i = ((C_{dl} + C_{gl} + C_{lr}) - v_i) + hl \quad (1)$$

Belowground C inputs in sugarcane has not been sufficiently investigated., neither in terms of root turnover nor of their lifespan in the soil (SMITH; INMAN-BAMBER; THORBURN, 2005).

A recent study by Otto (OTTO, 2012) assessing the effect of N fertilizer addition on the root dynamics of sugarcane ratoon, showed that root biomass increased in the first 9 months following the harvest of the initial sugarcane planting (PC1), subsequently decreasing until the harvest of the first ratoon cane (RC). Using data from Otto (2012) we calculated that between 55% and 65% of the sugarcane root biomass would die during each ratoon crop cycle. Using this proportion of root biomass we calculated the annual belowground root biomass carbon inputs to the soil as 55-65% of the total root dry biomass each year until the reformation stage.

To quantify the potential soil carbon stock changes from the above ground biomass inputs, we calculated the proportion of carbon that would be retained as soil carbon. This estimative was made using the C conversion ratio of 13% obtained by Robertson and Thorburn (2007).

To compare treatments, we performed an F-test of analysis of variance and then compared the average values of the aboveground biomass in each compartment, belowground biomass in each depth and S:R ratio among treatments using Tukey's test at a significance level of $p < 0.05$.

3.3 Results

3.3.1 Above and belowground biomass

There were no significant differences ($p < 0.05$) among the study areas either in total aboveground dry biomass and the individual biomass fractions, with the majority of the aboveground biomass coming from the stalks. Although the effects of sugarcane stage (plant or ratoon cane) were not significant there was a decreasing trend in the stalk dry biomass production, which is an indicative of declining stalk yields (Table 1). In PC the stalk:trash ratio was 0.81, decreasing to 0.77 and 0.69 in RC1 and RC4 respectively. This decrease in

stalk biomass is frequently observed in this crop and is a practical indicator of the need for reformation, as sugarcane yields decrease (MACEDO; SEABRA; SILVA, 2008).

Table 1 - Aboveground dry biomass productivity for each biomass fraction sampled and total dry biomass

Area	Dry leaves	Green leaves	Leaf roll	Stalk	Total dry biomass
----- Mg ha ⁻¹ -----					
PC	4.49 (0.5)	1.65 (0.4)	1.22 (0.3)	32.23 (6.8)	39.60 (7.1)
RC1	4.59 (0.9)	2.00 (0.5)	1.44 (0.4)	27.90 (7.6)	35.94 (8.5)
RC4	4.89 (0.6)	2.04 (0.2)	1.22 (0.1)	19.00 (4.8)	27.17 (4.8)

Means (n=3) followed by (S.D.) there were no significant differences between ratoon stages on aboveground biomass (Tukey's test at the 5% level)

For the belowground root biomass there was significantly ($p < 0.05$) greater dry root biomass in the surface 0-20 cm layer in PC and RC1 ratoon, decreasing with depth (Fig. 2). About 61 and 70% of the total root biomass was found in the top 20 cm respectively, the difference was not significant for the RC4 ratoon stage.

While the total root biomass (0-100 cm) did not significantly increase with increasing ratoon age, there was a significant ($p < 0.05$) increase in the root biomass over the 20-40 cm depth layer in the RC1 or RC4 stages, compared to PC.

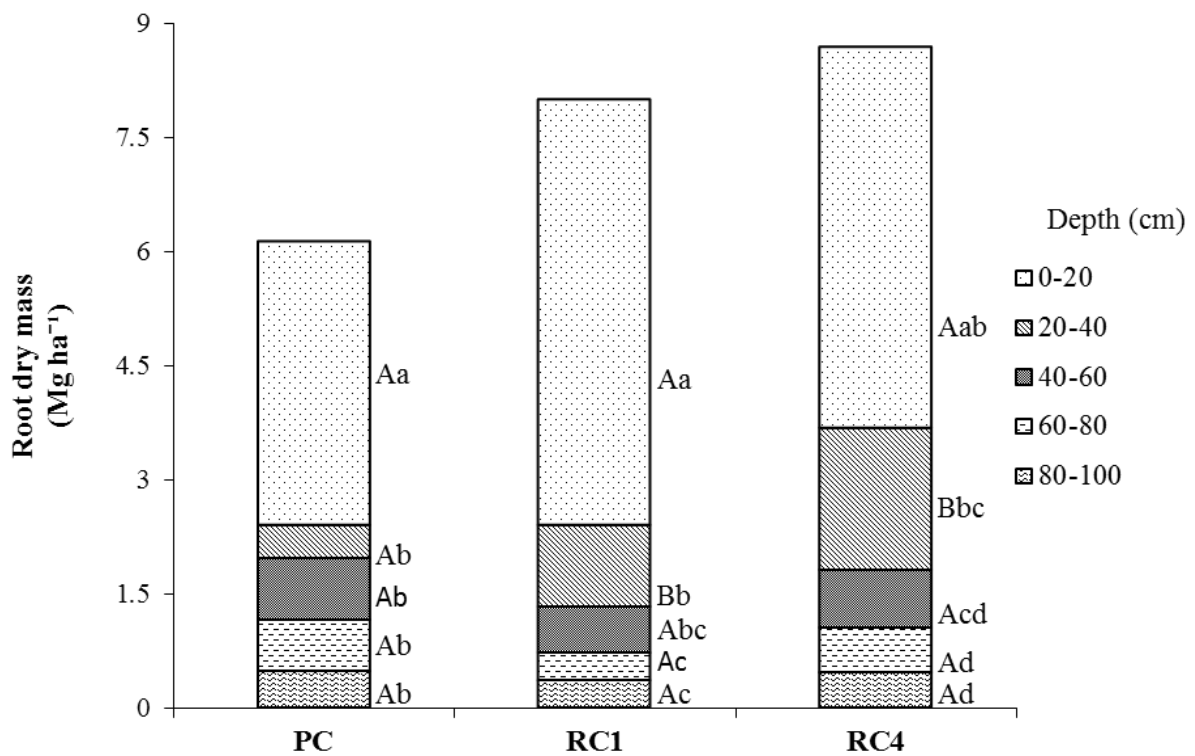


Figure 2 - Distribution of root dry mass (Mg ha^{-1}) in the soil to a depth of 100 cm in PC, RC1 and RC4 ratoon stages

* Lower case letters indicate statistical significance between root sampling layers within a ratoon stage. Upper case letters indicate statistical significance within a root sampling layer between ratoon stages ($p < 0.05$ Tukey's T test)

The S:R ratios at the peak standing crop were calculated as the aboveground biomass divided by the root biomass in 0-100 cm layers. There were no significant differences in that parameter within ratoon stage. However there was a trend for the S:R ratio to decrease with ratoon age, from $6.6 (\pm 1.7)$ in PC to $5.3 (\pm 3.0)$ and $3.4 (\pm 1.7)$ in RC1 and RC4 respectively.

3.3.2 Estimates of annual carbon inputs to the soil

Aboveground annual carbon inputs to soil in sugarcane plantations come from the residues of leaves, leaf roll and stalks that remain in the field after harvest. The carbon content and carbon partitioning in the sugarcane fractions are presented in Table 2. The total aboveground carbon inputs were calculated using eq. (1), accounting for harvest losses and vegetal impurities of 2.8% and 5.87 % respectively, that were measured during the harvest for the year studied.

The belowground carbon inputs from the roots were estimated as 55% and 65% of total root mass sampled at harvest for PC and RC1, assuming that the remaining root carbon (45-35%) is remaining as live roots (Table 2) (OTTO, 2012). The carbon inputs in RC4 is equal to the total carbon content of the root biomass in this stage, considering that the event of renovation of sugarcane planting usually happens after the harvest of that ratoon.

To account for the total carbon inputs throughout the sugarcane cycle from reformation, we calculated the carbon inputs above and belowground for the two sugarcane ratoon stages we did not measure (RC2 and RC3), using regression analyses from the biomass carbon over the ratoon stages we measured (Fig. 3). Over the sugarcane cycle (from planting to RC4) the total carbon inputs varied from 29.6 to 30.6 Mg C ha⁻¹ (1 sugarcane cycle of 5 years), corresponding to annual inputs of 5.9 and 6.1 Mg C ha⁻¹ year⁻¹.

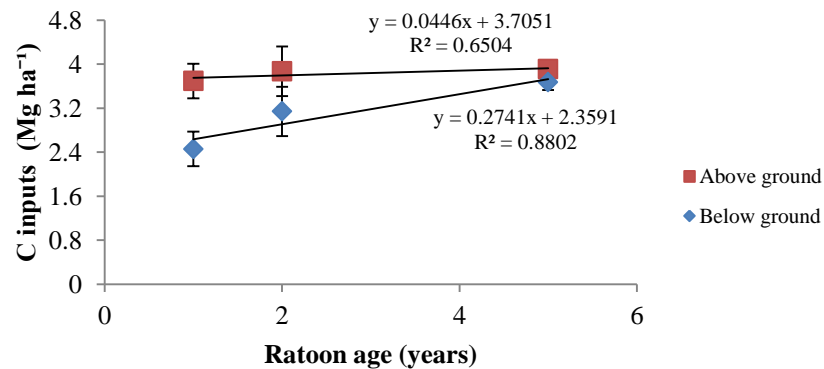


Figure 3 - Linear regression for above and belowground biomass carbon inputs with time (n=3, error bars are S.E.)

Table 2 - Carbon content, C partitioning and estimated annual C inputs to the soil for sugarcane crop. In the RC4 ratoon stage the below ground root inputs are 100% because the sugarcane undergoes reformation resulting total root death

	Dry leaves		Green leaves		Leaf roll		Stalk		C inputs			Total C Inputs	
									Aboveground	Belowground			
										55% ^a	65% ^a	55% ^a	65% ^a
	C %	C (Mg ha ⁻¹)	C %	C (Mg ha ⁻¹)	C %	C (Mg ha ⁻¹)	C %	C (Mg ha ⁻¹)	-----C (Mg ha ⁻¹)-----			C (Mg ha ⁻¹)	
PC	47.4 (0.8)	2.1 (0.3)	47.6 (0.4)	0.8 (0.2)	46.3 (0.3)	0.6 (0.1)	45.4 (0.4)	14.6 (3.0)	3.7 (0.5)	1.4 (0.2)	1.6 (0.2)	5.0	5.3
RC1	46.6 (0.7)	2.1 (0.4)	47.8 (0.3)	1.0 (0.2)	44.5 (0.9)	0.6 (0.1)	45.3 (0.02)	12.6 (3.4)	3.8 (0.8)	1.7 (0.7)	2.0 (0.8)	5.6	5.9
RC4	47.8 (0.3)	2.3 (0.3)	48.3 (0.6)	1.0 (0.1)	46.3 (0.3)	0.6 (0.07)	46.1 (0.2)	8.8 (2.2)	3.9 (0.2)	3.7 (1.2)	3.7 (1.2)	7.6	7.6

^a Considering a death rate of root system equal to 55% and 65%

We estimated the contribution of sugarcane residues in supplying C to the soil by using the C conversions ratio reported by Robertson & Thorburn (2007). From the measured above and belowground biomass carbon inputs and the assumed 13 % retained as soil carbon, we estimated that between 3.8 and 4 Mg C ha⁻¹ would be input to the soil during one crop cycle over 5 years. To account for the effects of reformation on the soil carbon stock inputs from above and belowground biomass (tillage impacts), measured CO₂ fluxes of 0.9 Mg C ha⁻¹ (SILVA-OLAYA et al., 2013) were used to calculate the net soil carbon changes, resulting in an net accumulation of 2.9 to 3.0 Mg C ha⁻¹ for each sugarcane cycle of 4 ratoons.

Using our measured data for above and belowground sugarcane carbon inputs (100 cm depth) and the ethanol offset of 9.8 Mg CO₂ ha⁻¹, we calculated payback times of 13 and 7 years for the carbon debt reported by Fargione et al. (2008) of 165 Mg ha⁻¹ of CO₂ associated with LUC into sugarcane from Cerrado wooded and 85 Mg ha⁻¹ of CO₂ for Cerrado grassland respectively (Table 3).

Table 3 - Sugarcane biofuel carbon debt and payback times accounting for sugarcane ethanol offsets (Original) and sugarcane ethanol offset plus net sugarcane carbon inputs to soil over an entire sugarcane crop cycle (Revised)

Sources	Net Carbon Inputs (Mg CO ₂ ha ⁻¹ yr ⁻¹)	Biofuel C debt (Mg CO ₂ ha ⁻¹)	Original Payback time (Years)	Revised Payback time (Years)
Sugarcane biomass C inputs ^a	2.1 – 2.2			
Sugarcane ethanol Offset ^b	9.8			
LUC Cerrado wooded ^c		165	17	13.7 – 13.8
LUC Cerrado grassland ^c		85	9	7 – 7.1
LUC Pastures ^d		70.2	7	5.8 – 5.9

^aMeasured sugarcane C inputs and payback times were calculated for Brazilian ethanol carbon debt in sandy soils

^bSugarcane ethanol offset according to Fargione *et al.* (2008) which does not include sugarcane biomass carbon inputs

^cTotal soil and biomass carbon debt presented according to Fargione *et al.* (2008), with land use change from Cerrado wooded and Cerrado grassland into sugarcane

^d Total soil and biomass carbon debt presented according to Mello et al. (2014) with land use change from pasture into sugarcane

3.4 Discussion

3.4.1 Above and belowground biomass

Despite that no significant effect of sugarcane stages on total aboveground biomass was found, we observed a decreasing trend in this variable over time which is typically observed in this crop, and is a practical indicator of the need for reformation of the sugarcane field followed by replanting (MACEDO; SEABRA; SILVA, 2008). Similar results for aboveground dry biomass for sugarcane RC2 and RC3 ratoon stages have been reported by Leite (2010) and Gava *et al.* (2001). However, Oliveira *et al.* (2010) studying the growth and dry biomass production in eleven varieties of sugarcane found values greater than reported here, with 70 Mg ha⁻¹ compared with 39.6 and 21.7 Mg ha⁻¹ for PC and RC4 ratoon stages respectively. These differences in aboveground biomass yield can be attributed to the influence of soil physical and chemical properties, weather, and the effects of land management practices (KRAVCHENKO; BULLOCK, 2000; SOUZA *et al.*, 2010; CERRI; MAGALHAES, 2012).

The partitioning of aboveground biomass between the stalk and trash (includes green leaves, dry leaves and leaf roll) provides the necessary data to develop and adjust ecosystem models that contain crop growth and yield modules for sugarcane. In our study the biomass fraction as stalk seems to be influenced by the sugarcane stage of development, decreasing with the ratoon, which is a indicative of declining stalk yields. These ratios are similar to the results obtained by Robertson *et al.* (1996), 0.8 in PC and RC cane with levels of biomass production of 50 Mg ha⁻¹ in Australian cultivars. Evensen *et al.* (1997), in a study of two Hawaiian cultivars, also found that the fraction of stalk in the aboveground biomass was relatively constant above a biomass productivity of 50 Mg ha⁻¹, with a fitted maximum Stalk to trash ratio of 0.66.

Converse to the observed trend of a decrease in aboveground biomass inputs, the root dry biomass (0- 100 cm) showed a trend to increase with the ratoon crop stages. These results contradict reports in which a decline in the root biomass in the ratoon stages are considered to be the cause of a decline in crop productivity compared to initial plant cane productivity (FERNANDES, 1979; LIMA *et al.*, 2002). Ball-Coelho *et al.* (1992), combining root sampling with soil coring to a depth of 2 m in an Ultisol in Brazil, found root biomass was greater during the ratoon cycle than at the end of PC cycle, in agreement with our results.

However, their values of root biomass were less than those presented here, 7.5 Mg ha⁻¹ and 9.0 Mg ha⁻¹ for plant cane and ratoon crop respectively. Those results can mainly be attributed to differences in soil texture as reported by previous research (ABAYOMI, 1989; COSTA et al., 2007). The sugarcane root system growth is highly dependent on the soil physical condition and clay content. In clay soil, Abayomi (1989) found that the root biomass was only 17 % of biomass founded in the sand soil for the plant-cane cycle, increasing to 59% in the second cycle.

Although there is less root biomass in the PC cane, its absorption efficiency per hectare is greater than at the ratoon stage, due to the presence of a new set of finer roots. The sugarcane ratoon root system has a greater proportion of older and lignified roots, whose maintenance requires an additional energetic cost, affecting the aboveground production (VASCONCELOS; GARCIA, 2005).

The methodology used to sample and then separate roots can have a significant effect on the results obtained (BOLINDER et al., 1999). The majority of studies to date restrict sampling to a depth shallower than 1 m, using techniques that do not quantify fine roots (FARONI; TRIVELIN, 2006; OTTO et al., 2009). Measuring root biomass under field conditions is difficult and consequently few publications have described the biomass production belowground for sugarcane. An accurate assessment of root biomass is essential to quantify total annual carbon inputs to soil from crops. The shoot to root ratios have been widely used in the absence of available belowground biomass carbon data (BOLINDER et al., 1999), for estimating carbon inputs associated with biofuel related life cycle analysis.

The distribution of roots in the different soil layers for sugarcane indicate that the majority of roots are in the surface 0-20cm, with 63% of the total root biomass in this layer and 77% in the surface 40 cm. Similar distributions (70-74%) of root mass were found by Evan (1938) (0-30 cm) and André et al. (2000) 0-85% (0-40cm) for sugarcane. Faroni (2004) and Vasconcelos (2000) evaluating the root distribution down to 80 cm, found 92 and 74% of total root biomass were in the surface 40 cm, and Ball-Coelho *et al.* (1992) reported root biomass in the range of 62 to 69% (0-50 cm).

Although there were no significant differences in the root system distribution in soil among crop cycles, there was a tendency for root accumulation in surface layers in the ratoon crop, which could have resulted from adverse soil conditions due to agricultural practices. Mechanized sugarcane harvesting decreases the water infiltration rate and increases resistance to soil penetration and bulk density (ANTWERPEN et al., 2008), thus affecting root growth

and development. Additionally the emergence of root from new shoots after harvest is carried out near of the surface. With increasing sugarcane harvest cuts after initial planting, the subsequent ratoon root system is located closer to the soil surface (HUMBERT; GALLARDO, 1974; CASAGRANDE, 1991; VASCONCELOS; GARCIA, 2005). Differences in root mass between crop cycles may also be the result of different climatic conditions that were prevailing during the crop cycle, in the immediate period anteceding the sampling time and field-management procedures (VASCONCELOS et al., 2003).

Few studies have reported S:R ratios for sugarcane, in our study there were no significant differences between ratoon stages after planting. This is reflected in the decrease in aboveground biomass (31%) and subsequent increase in the belowground root biomass of 29% from PC to RC4 ratoon stages. Using the S:R for assessing biomass carbon inputs would result in an underestimation of the total sugarcane carbon input to soil, as a greater proportion would be allocated to aboveground biomass that is removed during the sugarcane harvest.

Our estimates of S:R ratio under Brazilian conditions were generally higher than other values reported elsewhere, between 3 and 4.6 (INFORZATO; ALVAREZ, 1957; SUMAN et al., 2009; JANGPROMMA et al., 2012). Salata, Armene and Demattê (1987) studying five varieties of sugarcane verified that root biomass is on average 4.53% of aboveground biomass. Smith, (1998) apud Smith et al. (2005) assessed sugarcane responses to experimental manipulation of root:shoot ratios and concluded that sugarcane growth was consistent with functional equilibrium between roots and shoots. According to their results relative rates of shoot and root growth therefore tend to compensate for above and belowground constraints in order to maintain a balance between the functional capacities of the roots and shoot. In our study the root system accounted by 13 to 24 % of total sugarcane biomass from PC to RC4. These values are in agreement with average value of distribution of C allocation in sugarcane plant adopted by Vallis et al. (1996) in the parameterization process of Century sugarcane production model (15%).

The S:R ratio is an important parameter which is widely used in modelling studies in order to simulate the root system grow. Divergences between our results and values previously reported can be attributed to the effect of factors such climate, soil fertility and management on aboveground biomass production. In this way to compare S:R ratios values became difficult because of the influence of those characteristics inherent to each study site. Additionally, the methodology used to quantify root biomass also results in considerable variability in the S:R (CAMPBELL; DE JONG, 2001; BOLINDER et al., 2002).

3.4.2 Annual carbon inputs to the soil

Management practices, soil characteristics and climatic conditions can positively or negatively affect the rate of SOC accumulation. Predicting changes in soil C stocks, therefore, depends on reliable estimates of net primary productivity (NPP) and the proportion of the NPP returned to the soil and sequestered as SOC (PAUSTIAN; COLLINS; PAUL, 1997; CAMPBELL et al., 2000; BOLINDER et al., 2006).

We found that in the sugarcane production system under mechanized green harvesting, there were substantial annual C inputs, with potential beneficial effects on soil properties for plant productivity (TOMINAGA et al., 2002; MEIER et al., 2006; ROBERTSON; THORBURN, 2007), and carbon sequestration for the mitigation of GHG emissions associated with sugarcane production (GALDOS; CERRI; CERRI, 2009).

According with our estimates between 2.9 and 3.0 Mg C ha⁻¹ would be input to the soil during one crop cycle composed by 4 sugarcane ratoons treatments, which corresponds to 0.58 to 0.6 Mg C ha⁻¹ year⁻¹. These results are in the range of values found in literature, reported by Cerri et al. (2011), which showed a mean annual C accumulation rate varying from 0.7 in sandy soils to 2.0 Mg ha⁻¹ year⁻¹ in clayey soils in the 0-0.3 m soil depth, in areas under green harvesting system.

It is important to highlight that our estimates were performed using measured dry biomass data and C retention data obtained from the literature. Belowground C inputs may be underestimated considering that it involves two components: i) the root biomass at harvest, and (ii) the extra-root derived C produced throughout the growing season (i.e., root exudates and root turnover), which was not evaluated in this study. This latter source of carbon input into the soil has not been sufficiently investigated for sugarcane.

Land use change and energy crop expansion, including sugarcane, could result in a carbon debt, promoted by activities such as slash and burn of native vegetation (during the LUC) or by the decomposition of SOM (FARGIONE et al., 2008; LAPOLA et al., 2010). Fargione et al. (FARGIONE et al., 2008) reported that land use change from Cerrado wooded and Cerrado grassland to sugarcane and soybean crops result in a transient carbon loss of 165 and 85 Mg ha⁻¹ of CO₂ respectively. The payback times for the soil carbon debt in that study were calculated using the annual GHG equivalent offset for production of sugarcane ethanol of 9.8 Mg CO₂ ha⁻¹ (FARGIONE et al., 2008). Including our measured data for that calculation the

payback times are less than previously reported in 3.3 years for LUC into sugarcane from Cerrado wooded and 2 years for Cerrado grassland (Table 3) .

However that land use change process is not the situation properly involved in the expansion of agricultural production of sugarcane in Brazil. The National Supply Company (CONAB) reported that 78% and 72% of the expansions corresponding to 2008/2009 and 2009/2010 crop season respectively, occurred over pastures (CONAB, 2012; 2010). Mello et al. (2014) researching the modifications on the soil carbon stocks, as result of land use change due to sugarcane expansion, found that the conversion from pastures areas to sugarcane in sandy soils located within a radius of 30 km of our studied area (similar climatic conditions) caused an average loss of $11.1 \text{ Mg ha}^{-1} \text{ C}$ in an average time span of 16.5 years after conversion. Including the emissions from biomass removal, estimated as $8.05 \text{ Mg ha}^{-1} \text{ C}$ (CHANGE *et al.*, 2006), the carbon debt for this land use change increases to $19.1 \text{ Mg ha}^{-1} \text{ C}$ leading to a repayment time of 7.3 years. Including carbon stocks in above and belowground biomass, it would be necessary for 5.8 to 5.9 years to repay carbon emissions when pastures are replaced by sugarcane (Table 3).

The Brazilian government has recently conducted a study to establish Sugarcane Agro-ecological Zoning (ZAES) which considers environmental aspects to guide sustainable expansion of sugarcane production. In that study the areas were classified according to its edaphic-climate aptitude as areas with high, medium and low aptitude to sugarcane planting. According to ZAES about 62% of the area available to sugarcane expansion in the south central region of Brazil corresponds to the medium aptitude class, in which the experimental area fits due to its edaphic and climatic characteristics. About 59% of the areas grouped in this class are occupied by pastures.

While sugarcane expansion in Brazil initially causes soil carbon losses, with the adoption of the mechanized green cane harvesting system, the C fixed in plants by photosynthesis is added to soil as above- and below-ground litter contributing to increased carbon inputs and reduced payback times for the C debt incurred through LUC. By accounting for the additional carbon inputs due to the shift in sugarcane management to mechanized harvesting, the payback times for the biofuel carbon debt (FARGIONE et al., 2008) are reduced by 16-22%.

3.5 Conclusions

While aboveground biomass decreased with the number of ratoons, the total belowground biomass had a trend to increase with the ratoon crop, stage which most of the

root system were accumulated in the surface layers. In this sense, despite no significant differences were found, the shoot:root ratio showed a tendency of decreasing with ratoon age varying from 6.6 in PC to 3.4 in RC4.

Assuming a 13% of soil C retention we estimated a net C accumulation of 2.9 to 3.0 Mg C ha⁻¹ for a sugarcane cycle of 5 years; C inputs that when calculated together with the ethanol offset reduce the payback time of C debt to 13 and 7 years in the land-use transition from Cerrado wooded and Cerrado grassland respectively. Replacement of pastures by sugarcane has a low impact, with payback estimated in 5.8 to 5.9 years.

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4 MODELLING SOC VARIATION DUE TO LAND USE CHANGE AND MANAGEMENT PRACTICES IN SUGARCANE CULTIVATION IN SOUTH-CENTRAL BRAZIL

Abstract

Brazil stands out as the world's largest sugarcane producer and the second major supplier of ethanol. Due to the increasing demand for both products almost 3 million hectares of sugarcane were added to the production system in the last 5 years and other 9 million hectares are expected to be converted into sugarcane until 2019. These land-use transitions can affect the soil organic carbon (SOC) dynamic by decreasing the soil carbon (C) stocks and increasing the atmospheric greenhouse gases emissions. Here we used the Century ecosystem model in order to study the impact of land use change (LUC) due to sugarcane cultivation as well as to evaluate the effect of different management practices on long-term SOC dynamics. A soil data-set composed by 85 areas among sugarcane, pasture and annual crops were used for the 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 burning was simulated as the baseline system (SCB). Our results indicated that the model performance was good in replicating measured C stocks as well as reflecting the main trends of C stock variation due to LUC. Long-term simulations suggested that changes in the sugarcane harvest from burning to green harvesting increase the soil C stock at an average of $0.21 \text{ Mg ha}^{-1} \text{ year}^{-1}$. The addition of organic amendments such as vinasse and filter cake caused increases in the yield and reductions in the mineral N fertilization can be performed without affecting the production of the crop. The potential of C accumulation was projected to be higher when those industrial residues are added to the soil, varying between 0.34 and $0.37 \text{ Mg ha}^{-1} \text{ year}^{-1}$ in SC3 and SC2 respectively. The number of years necessary to restore the transient C loss due to the LUC varied with the texture, native vegetation and management scenario adopted. The model predicted that under SC1 the soil C stocks lost due to the conversion from pasture to sugarcane can be totally restored after 24 years in clay and loam soils under priority and regular suitability. Meanwhile sugarcane involving organic fertilization (SC2 and SC3) allows a reducing that time spans to 17 years in clay soils and 18 years in loam soils. Recovery the C losses in sandy soils will take a mean time of 24 years for all the suitability classes. Century model can be used as a tool to study the impact of different soil management in the SOC dynamics in sugarcane.

Keywords: Soil organic matter; Century model; Green harvesting; Sugarcane expansion; C stocks; Brazil

4.1 Introduction

Sugarcane crop is an important component of the Brazilian economy, supporting about 1.5 % of the Gross Domestic Product. This crop is commercially cultivated in Brazil as a

monoculture with a full crop cycle of six years, during which five harvests, four ratoon treatments, and one field renovation are performed.

Besides sugar production, sugarcane is also used to produce ethanol. Currently, more than 50% of the sugarcane crushed in Brazil is being distilled into ethanol (CONAB, 2013), one of the most sustainable biofuels currently produced at commercial scales and whose crescent demand has caused considerable increases in the sugarcane planting, which reached 10 Mha during the last harvest season (CONAB, 2013).

Future projections of the sugarcane sector aim to increase the ethanol production to 58.8 billion of liters in the next 5 years, a value that corresponds to more than twice the yield registered in the year 2008. To achieve those national goals the planting area for sugarcane should reach the significant level of 19 Mha (BRASIL, 2009; CERRI et al., 2010).

Although those expansion processes would favor ethanol production, land use change (LUC) can affect the greenhouse gases (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 (LAL; KIMBLE, 1997; SIX et al., 2002) and increases in atmospheric GHG emissions.

Studies indicate that energetic 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 for conversions 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). Conversely, when sugarcane replaced annual cropland, the soil C stocks increased by 17 % in the 0-30 cm depth layer (MELLO et al., 2014).

Conservational management practices in sugarcane crops can contribute to the C restoration lost through land cultivation, diminishing the impact of LUC processes. The conversion from manual harvesting involving pre-harvest burning to mechanical or green harvesting leaves considerable quantities of dry matter on soil surface which provides several potential benefits to the system (CEDDIA et al., 1999; GRAHAM; HAYNES; MEYER, 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 C accumulation is highlighted (CANELLAS et al., 2003; ROBERTSON; THORBURN, 2007; GALDOS, CERRI; CERRI, 2009; 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 the sugarcane fields, can potentially affect the soil organic carbon (SOC) dynamics enhancing soil quality and crop production (FLIEßBACH; MÄDER, 2000; CANELLAS et al., 2003; DE RESENDE et al., 2006; ZOLIN et al., 2011; DE SOUZA BARROS et al., 2013; DA SILVA, BONO; DE AR PEREIRA, 2014).

Although such benefits from management, soil organic matter is also affected by soil characteristics (texture and mineralogy) and climate conditions. The potential of a given soil to store C is highly variable; subsequently the analysis of an agroecosystem dynamics is difficult because of intrinsically complex interactions between its components (TORNQUIST; MIELNICZUK; CERRI, 2009).

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 the nutrients dynamics. Prediction of future agroecosystems states are important aspects of model application (KRULL; BALDOCK; SKJEMSTAD, 2003) which can drive decision makers and planners to develop sustainable soil management systems thereby insuring proper GHG mitigation measures.

In this study we used the Century model to access the impact of LUC related to sugarcane expansion in south-central Brazil, as well to evaluate the effect of different management practices on long-term SOC dynamics. The Century model is an ecosystem-level model for the plant–soil system that simulates carbon and nutrient dynamics (METHERELL et al., 1993). Although it was originally developed for modelling soil nutrient dynamics in grassland systems, it has been considerably modified since its first version for application in crops, pasture and forest systems (PARTON; RASMUSSEN, 1994; KELLY et al., 1997; PENG et al., 1998; KIRSCHBAUM; PAUL, 2002). Model simulations in tropical and subtropical conditions also have been performed indicating good results (CERRI et al., 2004; LEITE et al., 2004; GALDOS et al., 2009; TORNQUIST; MIELNICZUK; CERRI, 2009; BORTOLON et al., 2011).

4.2 Material and Methods

4.2.1 Study region, land use and soil management

The study area involved eleven counties distributed over the south-central region of Brazil (Fig 1) which is the main area of production of sugarcane (79% of the Brazilian production in

2011/2012 season) and covers approximately 30% of the national territory. Due to its extension the climate of the region varies in a wide range involving; i) Tropical moist (Aw, Koppen) with dry winter, precipitations 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 precipitations well distributed over the year, and subtropical with a dry winter (Cwa, Cwb Koeppen) and a warm or hot summer with heavy precipitation during the summer.

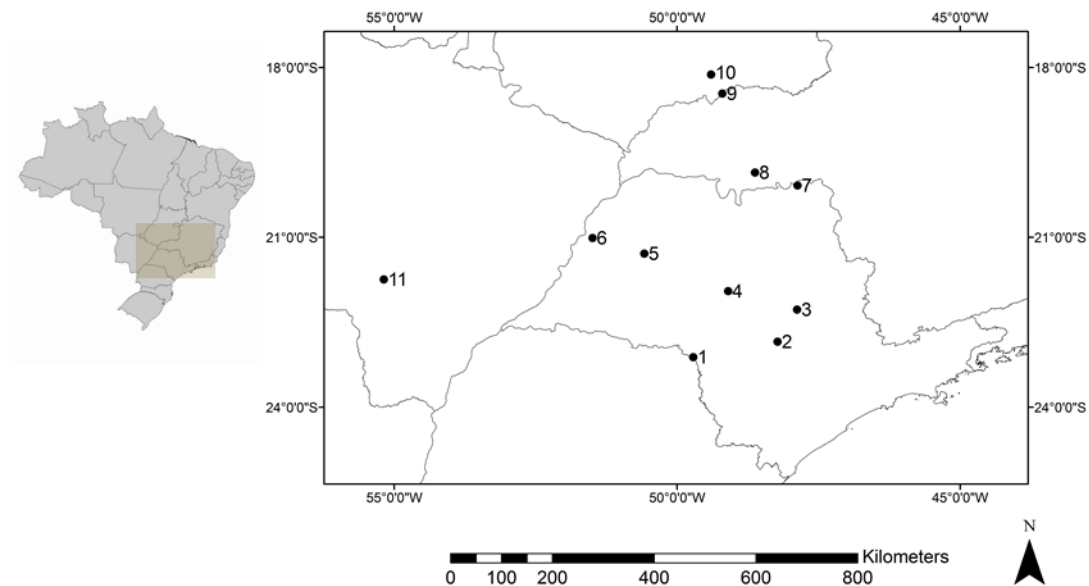


Figure 1 - Regions in south-central Brazil selected for modelling of the soil C dynamics: ¹⁻⁷São Paulo (SP); ⁸⁻⁹Minas Gerais (MG); ¹⁰Goiás (GO); ¹¹Mato Grosso do Sul (MS)

The complexity of landforms, climate, and rock types in the central south region results in a wide variety of soils, which can be grouped into eleven classes. 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 containing 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 phytophysionomy 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) apud De Castro; Kauffman, (1998) 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 variations, including coastal (3 to 50 m), submontane (50 to 500 m), montane (500 to 1,200 m), and high montane (1,200 to 1,400 m) forests, creating a vegetation gradient ranging from shrubs to well-developed montane forest (DE GUSMÃO CÂMARA, 2003).

Both the Cerrado and the Atlantic Forest ecosystem have been the object of land cover changes. Cultivated pastures (mostly *Brachiaria* spp.) and cropping systems are the dominant anthropic landscapes in the Cerrado, occupying 26.5% and 10.5% respectively (SANO et al., 2008). Traditionally, at the conversion from native vegetation to pasture, pastures are established after clearing and burning without chemical fertilization before planting. According to (JUNIOR; VILELA, 2002) more than 70% of snow 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 aptitude of the central-south region, the pastures are being replaced for the sugarcane crop. 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 over pastures (CONAB, 2010, 2012).

Sugarcane is a 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; SEABRA; SILVA, 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 the burning practice has decreased significantly in preference to the implementation of green systems, where large quantities of residues remain 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 2011-2012 crop season involved mechanical harvest without burning (HARTEMINK, 2008), and this tendency will continue in order to improve the environmental aspects of sugarcane production and to attend to global market politics.

4.2.2 Soil database

The soil data used in this study were reported by Mello et al. (2014) and involved 63 areas where sugarcane replaced pastures (55), agriculture (5) and native vegetation (3); 32 areas of pastures, 5 areas of agriculture and 8 areas of native vegetation which were used by the authors as comparison pairs (Appendix B).

4.2.3 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. The Century is composed for different sub-models involving aspects related to the soil organic matter (SOM) decomposition, soil water balance and vegetal production of crops, grassland and forest systems.

The SOM sub-model includes five pools, two of them represent the litter and three represent the SOM. Vegetal and animal residues are divided in structural and metabolic pools as a function of the lignin:N ratio. The SOM is divided in three fractions with different potential decomposition rates: i) Active fraction, which represents microbial biomass and metabolites which turnover 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 turnover on time scales of centuries.

The water balance sub-model calculates the monthly evaporation and transpiration water loss, the water content of the soil layers and saturated flow of water between soil and layers.

The vegetal production sub-model simulates the dynamics of plant production in different ecosystems: grasslands, agricultural crops, forest and savanna systems. It calculates the maximum monthly plant production as controlled by moisture and temperature, when there is no nutrient limitation.

4.2.4 Model Initialization and Parameterization

The initialization of the model consists in the input of site-specific data involving soil and climate parameters. Soil characterization included soil texture (sand, silt, and clay content), bulk density, soil depth, pH and total soil C and N content. Climate inputs involved monthly precipitation and mean maximum and minimum monthly temperatures according to observations made at the meteorological station closer to the study area, data provided by *Agrometeorological Monitoring System (AGRITEMPO)*.

The parameterization or calibration of the model is a fundamental part of modelling studies which aims to improve the correlation between measured data and simulated output by tuning internal model parameters (GOMES; VARRIALE, 2001). In this study we adjust the parameters of the model for each one of the systems simulated based on information in the literature:

4.2.4.1 Forest calibration

In order to initialize the model prior to simulating forest clearing and pasture and/or sugarcane establishment, we used the Century forest sub-model 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 death rate for leaves was calibrated as the average of the values quantified by Valenti, Cianciaruso and Batalha (2008) and Silva et al. (2007) and the lignin content in leaves and trunks were adjusted to 29.6% and 26% respectively (SILVA et al., 2007; DO VALE; DIAS; SANTANA, 2010).

Since the nitrogen atmospheric deposition and biological N fixation rates have a significant influence on the estimates of soil carbon, we set those parameters to the typical values found at that ecosystem: $0.5 \text{ g m}^{-2} \text{ year}^{-1}$ for N atmospheric deposition (BUSTAMANTE et al., 2012) and $0.002 \text{ g m}^{-2} \text{ year}^{-1}$ 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; KAUFFMAN, 1998) which causes losses of 33% of aboveground biomass as exposed by De Castro and Kauffman, (1998) and a tree mortality and subsequent tree-fall and gap formation every 120 years, event 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 parameters. The model was run involving 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 the calibration performed by Cerri et al. (2004).

4.2.4.2 Pastures and Annual crops

To adjust the model for pasture conditions we used the biomass productivity data reported by Lilienfein; 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 aboveground crop potential monthly production in order 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 performed in Brazil (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.

4.2.4.3 Sugarcane crop

The sugarcane crop was simulated using the vegetal production sub-model for forest, through which it is possible to parameterize the aboveground productivity for each vegetal compartment of the plant (leaves, tops and stalk).

The parameters of optimum and maximum temperature for production were adjusted to 30°C and 45°C respectively (GALDOS et al., 2009). The distribution of aboveground and belowground biomass was calibrated based in data obtained from biometric measurements reported at the chapter two of this thesis 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 compartment of the plant were adjusted according to data found in vegetal samples collected in three areas of sugarcane planting

involving the same sugarcane variety (RB86-7515) and similar soil, climate, topography and management, which were located near to Piracicaba, in northeastern São Paulo State, Brazil.

The potential biological N fixation rate was specified as reported by Galdos et al. (2009). 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 following the historical report of management: i) Manual harvest preceded by burning of the dry leaves and tops and ii) Mechanical harvest or green harvesting where the leaves, tops and variable quantity of pieces of stalks are retained in the field forming a thick mass of 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 cutting events in forest systems.

The impact of fire on the vegetation and litter was set based on field experiments with controlled pre-harvest fires performed by Ball-Coelho 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, are 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 adjusted as 36%, mean value found in those studies.

In the green harvesting system the model was set to remove 99% of aboveground biomass, which 94% of dry matter regarding to tops and leaves and 2.8% of stalks return to the system as litter after the harvest. Those percentages were established based on data of harvest losses involving 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 is poorly understood. Some studies have stated that after the first sugarcane harvest the original root system quickly becomes non-functional and dies (BAVER et al., 1962). However other studies reported that part of the root system remains active after the harvest of stalks (WOOD; 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 the management history some of the study areas had organic amendments over 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 a form of

cycling organic matter. In the Century model those organic matter additions were performed through the “omad.100” functions in which the timing, rate, and composition of the residue applied were set based on the calibration performed by Galdos et al. (2009b).

The 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 “conventional” and “minimum” default tillage parameters specified at the Century 4.6.

4.2.5 Model Validation

Evaluation of model performance is often based on a graphical comparison of the simulated values produced by the model with values resulting from field measurements. To validate the model, we compared the model output of total SOC to a set of data which were not used in the calibration phase.

For a more quantitative comparison of measured and simulated data we performed a statistical analysis as suggested by Smith et al., (1997), which involved the following test statistics: sample correlation coefficient (r), coefficient of determination (CD), root mean square error ($RMSE$), and mean difference between observations and simulation (M).

4.2.6 Future scenarios and long-term soil C stock prediction

According to data reported by CONAB the planting area of sugarcane has increased by 2.9 Million hectares since the harvest of 2006/2007 to 2011/2012. More than 95% of that expansion has occurred in the south-central region of the country, where 70.8% and 17.5% of areas dedicated to pasture and annual crops production has been replaced respectively.

Nassar et al. (2008) expressed that in the year 2018 the sugarcane planting area is expected to reach a level of 11.7Mha, which should follow the trend of LUC observed in the past, where the pastures were the main system of land use replaced by sugarcane.

Regarding the harvest system, the data reported by CONAB showed an increase in the adoption of green harvesting in the south-central region from 28.6% to 71.6% during the last 6 harvest seasons. In Sao Paulo state, the main state producer of sugarcane, the 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 that there is not legal

restrictions regarding the sugarcane pre-harvest burning in other states of Brazil, the statistical data indicates an important decrease in this practice during the past years in the states of Parana, Minas Gerais, Matto Grosso and Goias in an average of 52%.

In this sense, a series of 50-year projections were generated in order to access the impact of different scenarios of management systems involving green harvesting on the long-term soil C dynamics at each site. The sugarcane burning system was used as the baseline system (SCB) for comparisons.

Long-term soil C prediction was performed considering the land use history of all the areas simulated. This way, the mean year of establishment of the pastures and agriculture as well the number of years under each management before sugarcane planting were estimated. In the areas where the sugarcane was established over pastures the simulation of future scenarios of management in sugarcane crop started to be performed after simulating 11 years of burning. In areas previously occupied for the production of annual crops the future scenarios were simulated after a 3 year burn period.

Simulated future scenarios:

1. Green harvesting (SC1): The adoption of green harvesting system in sugarcane crop, where the leaves, tips and variable quantity of pieces of stalks are retained in the field forming a thick mass of mulch 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).
2. Green harvesting + OMAD (vinasse and filter cake) (SC2): Organic amendment inputs such as vinasse and filter cake were simulated for all the study areas. Typical application rates of those residues in Brazilian sugarcane fields: $205 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ of vinasse and 9 Mg ha^{-1} of filter cake at cane plantations during reformation periods, were considered for this scenario.
3. Green harvesting + Low N inputs (SC3): Studies conducted in Brazil and Australia have highlighted the potential reduction of N rate fertilization in the ratoon cane with green harvesting (VALLIS et al., 1996; ROBERTSON; 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 $36 \text{ kg ha}^{-1} \text{ year}^{-1}$. Regarding the sugarcane plant, Nunes Júnior (2005)

apud Favero (2007) expressed that the application of 5 Mg ha⁻¹ of filter cake could supply 100% of N needs of the crop. In this context we simulated lower mineral and organic N inputs: 5 Mg ha⁻¹ of filter cake (Non N fertilization) in plant cane and 70 kg ha⁻¹ year⁻¹ of mineral fertilizer in ratoon cane.

4.3 Results

4.3.1 Model performance

The model estimates were in agreement with the field-observed SOC stocks in all systems of production, pastures areas as well annual crops and sugarcane areas (Fig 2). The maximum variation between the measured and simulated data found under pasture, annual crops and sugarcane conditions were 14.0 Mg ha⁻¹, 11.6 Mg ha⁻¹ and 21.0 Mg ha⁻¹ respectively. The mean difference between the measured and simulated results was 3.17 Mg ha⁻¹ in sugarcane and -0.37 Mg ha⁻¹ and 1.73 Mg ha⁻¹ in pastures and annual crops.

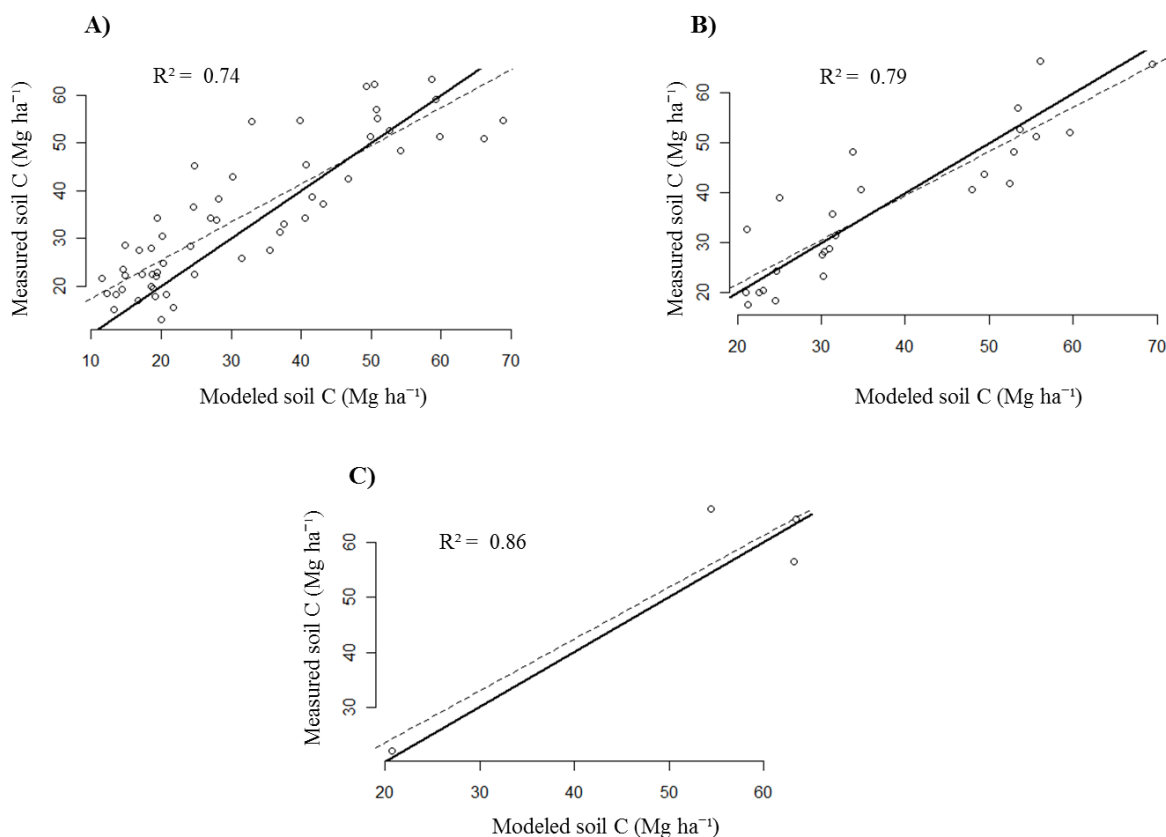


Figure 2 - Linear regression between measured and simulated soil C stocks in sugarcane (A), pasture (B) and annual crops (C) conditions

The results from the statistics test indicate that the model performance was good in replicating measured C stocks (Table 1). The coefficient of correlation (r) between measured and simulated data is near to 1 in all the conditions simulated, indicating a positive degree of association between simulated and measured values. 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 better than the mean of the observations.

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

In addition to the statistical tests, the performance of the modelling was accessed through the analysis of the temporal dynamic of the simulation results. It is important that a valid model reproduce not only the final system response but also its temporal trajectory. The best modelling process is one that is able to reflect the real dynamic of SOC in different ecosystems.

In this research, despite the absence of SOC stocks data under native vegetation in all study areas for validation, we verified that the C stocks simulated in the equilibrium condition were higher than those found in pastures and annual crops, decreasing over the time in function of the management practices simulated in each situation.

The conversion from native vegetation to pastures resulted in mean rate of C losses of $0.19 \text{ Mg ha}^{-1} \text{ year}^{-1}$, a value lower than that found when annual crops are established after clearing the native vegetation (1.14 Mg ha^{-1}).

When pastures precede the planting of annual crops we verified an annual increase of 0.11 Mg ha^{-1} in the C stock. Conversely, C depletion was observed for the establishment of Integrated crop-livestock management systems - ICL - (pasture-annual crop rotation) proceeding the clearing ($0.47 \text{ Mg ha}^{-1} \text{ year}^{-1}$).

Regarding the land use change (LUC) for planting of sugarcane we verified that the conversion from pasture to this crop resulted in a mean rate of C losses of $0.49 \text{ Mg ha}^{-1} \text{ year}^{-1}$, reduction which represents a soil “carbon deb” of $27.19 \text{ Mg ha}^{-1} \text{ C-CO}_2$. Higher C depletion was estimated for sugarcane planting over areas involving ILC ($2.7 \text{ Mg ha}^{-1} \text{ year}^{-1}$) and opposite trend (C accumulation) was observed when sugarcane occupied areas used for the production of annual crops ($0.10 \text{ Mg ha}^{-1} \text{ year}^{-1}$).

4.3.2 Long-term Soil C stock prediction

Once verified, the performance of the modelling process we proceeded to simulate different management scenarios in each site for a time span of 50 years in order to view the impacts of those agriculture practices on SOC stocks.

Subsequently, the study areas were grouped according to the classification of suitability proposed by the Sugarcane Agro-ecological Zoning in Brazil (ZAE), which considers environmental aspects to guide sustainable expansion of sugarcane production. Three land use systems (patures, agriculture and integrated crop-live stock) and eight classes of suitability varying from high or prioriry suitability to unsuitable (due to the weather and/or soil conditions) were identified by the ZAE. More than half of the area available for sugarcane expansion is under pastures managmenet (57.2%) and 92% of those present regular suitability (61.4%) and priority suitability (30.4%).

In this way, we estimated the mean C stocks for the classes of suitabilty covered by the data-set where sugarcane replaced pastures areas. Only two study points were located in areas classified as unsuitable due to climatic restrictions related to possible frost conditions. Finally we group the soils according to the textural classes according to the Brazilian soil Classification system (SBCS – Portuguese acronym) (Fig 3).

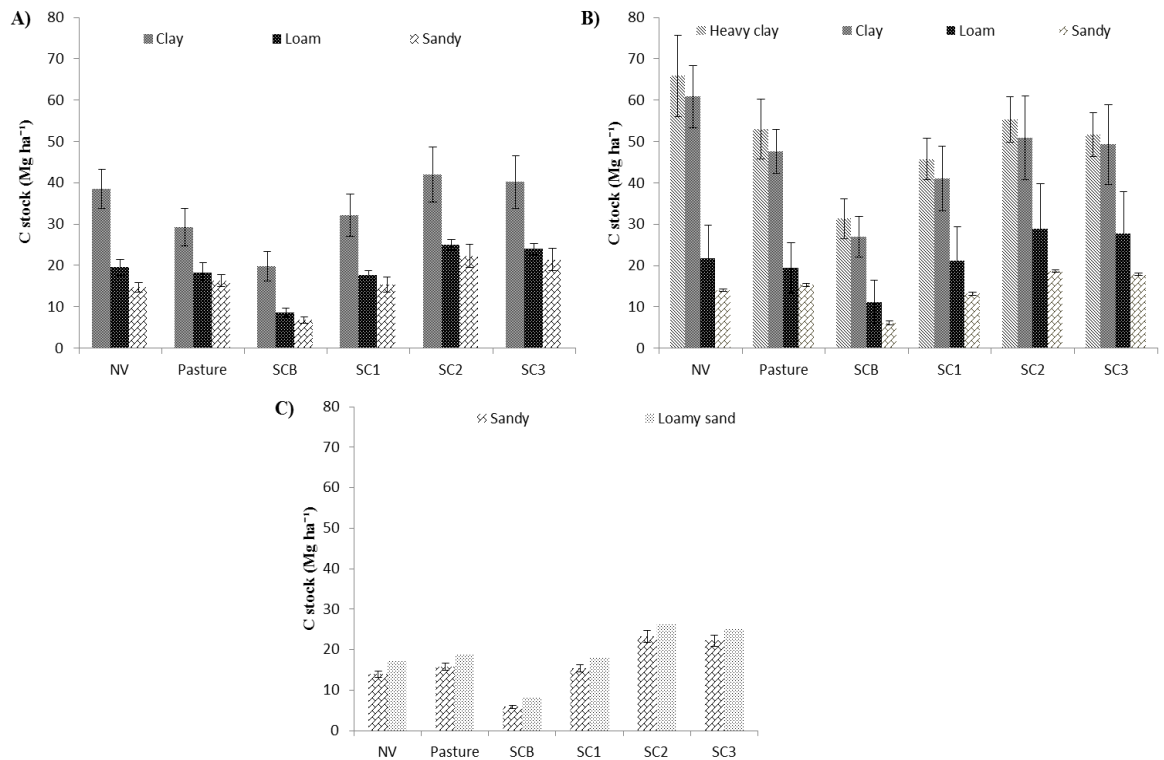


Figure 3 - Projections for soil C stocks (0 – 20 cm depth) in native Vegetation (NV), pasture and different scenarios of sugarcane crop management in south-central Brazil. (A) Areas under pasture with priority or high suitability; (B) Areas under pasture with regular suitability and (C) Areas under pastures with low suitability

For the study areas of regular suitability we estimated the mean C stocks over the projected time-span (50 years), factoring the areas in two contrasting textural soil classes: sandy and clay soils (Fig 4). The C stock measured in two areas of the data-set and values reported by Brandani et al. (2014) in locations with similar historical of management to that projected, were also included in the figure as a comparative points.

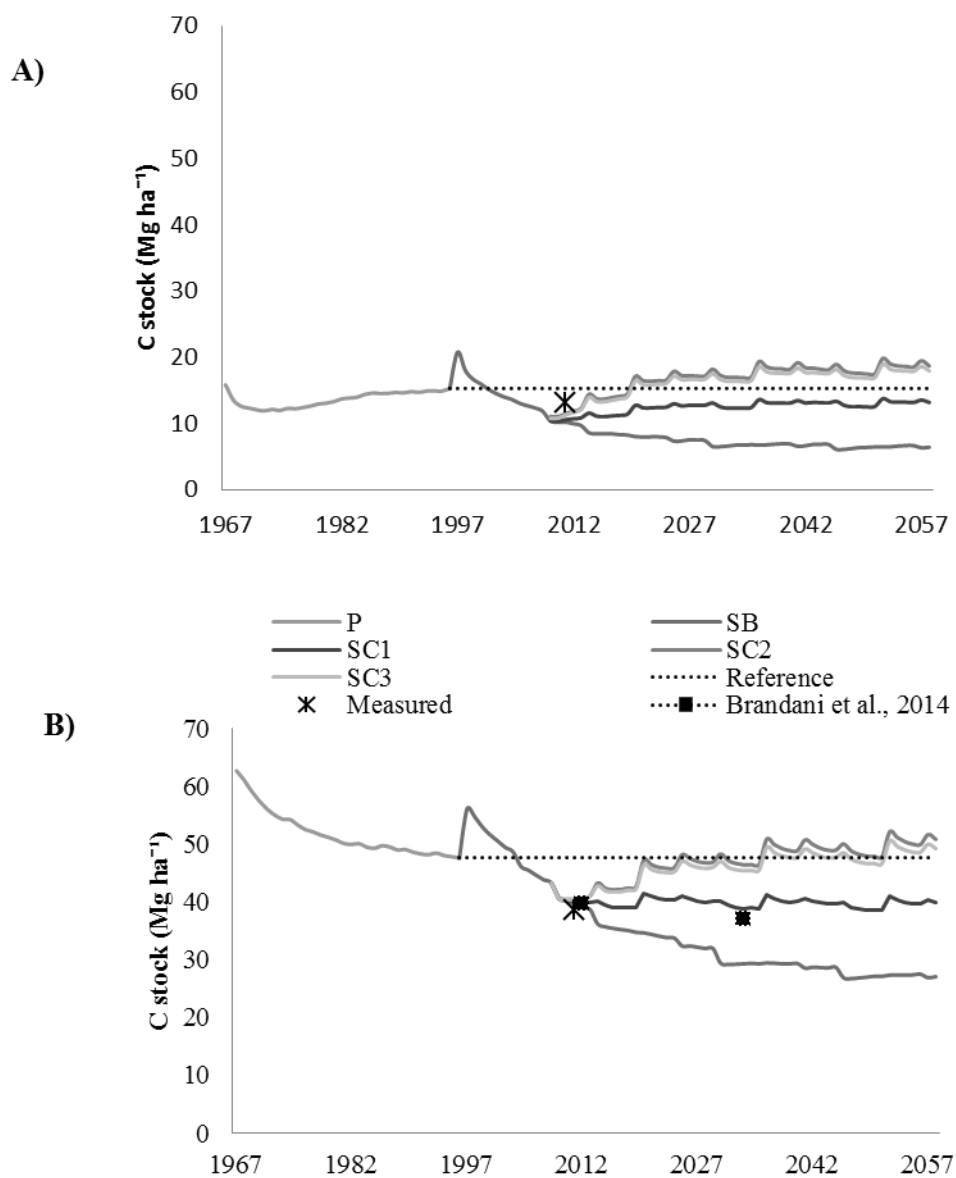


Figure 4 – Long-term soil organic C dynamics due to the conversion from pasture (P) to sugarcane involving different scenarios of management in sandy (A) and clay (B) soils in “Regular suitability” area to sugarcane expansion

C losses (negative values) and gains were calculated in all suitability classes (Table 2). The change in the harvest system from pre-harvest burning to green harvesting results in C stocks increases ($0.21 \text{ Mg ha}^{-1} \text{ year}^{-1}$), and varies as a function of clay content. The potential C accumulation is still higher when the production of sugarcane adopts organic amendments.

Table 2 - Soil C stocks variation as a function of transition from pasture to sugarcane involving pre-harvest burning (P – SB) and from pre-harvest burning to different scenarios of 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 -----			
Clay	-0.18	0.25	0.44	0.41
Loam	-0.19	0.18	0.33	0.31
Sandy	-0.19	0.17	0.31	0.29
	Regular suitability			
Heavy clay	-0.43	0.29	0.48	0.41
Clay	-0.41	0.28	0.48	0.40
Loam	-0.17	0.18	0.33	0.31
Sandy	-0.18	0.14	0.25	0.24
	Low suitability			
Loam	-0.20	0.19	0.35	0.33
Sandy	-0.21	0.20	0.36	0.34

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 (time span for soil C restoration). With the SC1 the C stocks reach the value before the conversion in two soil textural classes: clay and loam under priority and regular suitability respectively (Table 3). Sugarcane organic fertilization (SC2 and SC3) allows for reduction of the time-span by 29% in clay soils and 25% in loam soils. In other textural classes changing the harvest system is not enough to recover the losses of C.

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

Texture	SC1	SC2	SC3
Priority suitability			
Clay	24	17	17
Loam	N/A *	18	24
Sandy	N/A	24	24
Regular suitability			
Heavy clay	N/A	40	40
Clay	N/A	40	40
Loam	24	18	18
Sandy	N/A	24	24
Low suitability			
Loam	N/A	24	24
Sandy	N/A	24	24

*N/A means times span higher than simulated

Since the management practices projected in the SC3 appeared to contribute to the soil C restoration, we decided to simulate two sub-scenarios involving those practices and trash removal from the field. Recently, the Brazilian sugarcane sector has started considering the use of trash to cogenerate electricity and, in the coming years for production of second generation ethanol. Due to the positive impact of residues retention in the soil there is a concern regarding how trash removal can affect the SOM dynamics.

In this context two percentages of trash removal were modeled for the areas classified as “Regular Suitability”, which represent the main suitability class available for sugarcane expansion: i) SC3A, where 50% of the sugarcane residues resulting from green harvesting remain in the field and ii) SC3B where 30% of post-harvest sugarcane residues are removed for industrial processing purposes.

According to the Century estimates the more trash is removed the higher decreasing rate in the potential accumulation is expected (Table 4). In clay soils the trash removal impact is greater than in sandy soils.

Table 4 - Variation rate in the potential C accumulation projected for the SC3 due to trash removal in sugarcane areas

Texture	Sub-scenario	
	SC3A	SC3B
	-----Mg ha year⁻¹ ----	
Heavy clay	-0.10	-0.06
Clay	-0.10	-0.06
Loam	-0.08	-0.05
Sandy	-0.06	-0.03

4.4 Discussion

4.4.1 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. The statistical analysis of the performance of the modelling verified the accuracy of the simulations.

The simulated quantities of soil C stock in pasture and annual crops fit the measured data reasonably well ($R = 0.89$ and 0.93 respectively). According to the EF value, under those conditions the model described the trend in the measured data better than the mean of the

observations. 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, although the model performance was good in replicating measured 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; the RMSE value was higher than in pasture and annual crops, lying outside the 95% confidence interval of the measured data. However, bias in the distribution of predicted values with respect to measured values was not detected since E value was lower than E95 %.

Even though we have no aboveground plant productivity measurements for each one of the study areas, the simulated average stalk yield (96 Mg ha^{-1}) was consistent with the mean yield reported for the last 5 harvesting seasons in south-central Brazil (80.24 Mg ha^{-1}) (CONAB, 2013), which verify the performance of the vegetal production sub-model to simulate the dynamics of the agroecosystem.

The trend of SOC over the time was also replicated by the model. Stocks measured revealed that LUC led to a decrease in C content compared with that in the natural undisturbed condition, a situation that was observed in the modelling. 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 effects of land conversion from forest to cultivated land concluded 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 50% in the first years of cultivation due to several processes, including microbial decomposition and erosion (MIELNICZUK; SANTOS; CAMARGO, 1999).

The rate of losses is influenced by the type of native vegetation, climate, soil and management practices (DAVIDSON; ACKERMAN, 1993; BRUCE et al., 1999). The conversion from forest to pastures lands can lead to either a positive or negative impact on the overall change in soil C. Cerri et al. (2006), upon reviewing data obtained in literature, found that soil C stocks of two-thirds of pastures increased in comparison to native vegetation in the Amazon region. Increases in the soil C by 2.7 to $6.0 \text{ Mg ha}^{-1} \text{ year}^{-1}$ 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 indicated mean annual C losses of 0.19 Mg ha^{-1}

when pastures are established after clearing the native vegetation. Those results are consistent with the decreasing rate in degraded pastures reported by Maia et al. (2009) in a study performed in Brazil involving Amazon Forest and Cerrado vegetation ($0.28 \text{ Mg ha}^{-1} \text{ year}^{-1}$). According to the authors the variation in the C content was affected by the forage management as well as by the soil type since C depletion was observed in non-degraded pastures on Oxisols ($0.03 \text{ Mg ha}^{-1} \text{ year}^{-1}$) but C accumulation under other types of soils, mostly Ultisols ($0.72 \text{ Mg ha}^{-1} \text{ year}^{-1}$). 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 breeding. More than 70% of the total areas under cultivated pastures show some degree of degradation (MARTHA JUNIOR; VILELA, 2002; BATLLE-BAYER; BATJES; BINDRABAN, 2010), a process which is caused by inappropriate management of the system. 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 results of conversion to annual crops planting were variable due to the divergence in the management history. The model indicated C losses of an average of $1.14 \text{ Mg ha}^{-1} \text{ year}^{-1}$ when annual crops are established after clearing native vegetation. Conversion from native vegetation to agriculture is known to reduce the C stocks in the soil. 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 decreasing indicated by the model is in the average of values reported by studies previously developed in Brazilian Cerrado region (JANTALIA et al., 2007; CARVALHO et al., 2010). However it can be considered high when compared to other research which reported minimal differences between these systems (BAYER et al., 2006; MARCHÃO et al., 2009; FIGUEIREDO et al., 2013). This trend can be attributed to the long-term (~10 years) planting of soybeans crops once per year with conventional tillage, a practice which when simulated result in lower C input and higher mineralization rates.

Conversely, integrated crop-livestock (ICL) management systems can positively affect the soil C according to the century estimates. These systems combine crops and grasses as well as improve management practices in order to enhance animal production and reduce pasture and soil degradation, resulting in higher C stocks than in native vegetation. Salton et al. (2011) carried out a long-term experiment the C variation due to different land use system including ICL. The authors estimated changes in soil C stocks varying from -0.7 to 0.34 Mg ha⁻¹ year⁻¹ due to replacement of native vegetation for ICL systems. When compared to other management practices, such as no-till and conventional tillage, the ICL presented potential C accumulation, functioning as a sink of atmospheric CO₂. Similar results were reported by Carvalho et al. (2010) whose study quantified annual soil C increases between 0.8 to 2.8 Mg ha⁻¹ because of the adoption of ICL management.

Regarding the sugarcane planting, the Century model indicated different trends as functions of the previous management. Conversion from pastures caused a mean rate of soil C depletion of 0.49 Mg ha⁻¹ year⁻¹. Meanwhile the LUC from annual cropland to sugarcane had a positive impact resulting in C accumulation. Those processes of LUC associated to the sugarcane expansion are an important aspect which affects the greenhouse gases (GHG) balance of that energetic crop and consequently the carbon footprint of the ethanol. Previous studies have indicated that energetic crop expansion may result in carbon debt (FARGIONE et al., 2008; LAPOLA et al., 2010) which is caused by the C losses in CO₂ form promoted by the slash and burning of native vegetation and/or by the decomposition of SOM by natural agents.

In this study we estimated soil C debt of 27.19 Mg ha⁻¹ C-CO₂ due to 14 year time span of sugarcane planting over previous pastures areas. LUC from ICL systems conversion to sugarcane resulted in 20.9 Mg ha⁻¹ C-CO₂ of C debt over 4 years. Those C losses can be explained by lower C inputs in sugarcane crop resulting from pre-harvest burning, a practice which was adopted in more than 70% of the run-time simulated in both conditions. Additionally, sugarcane fields pass through a cultivation cycle every four ratoons cultivation treatments, which according to field measurements cause the emission of 3.5 Mg ha⁻¹ C-CO₂ (SILVA-OLAYA et al., 2013); meanwhile either pastures or ICL remain for long periods without any soil tillage.

In contrast to conversions from pastures and ICL the LUC from annual cropland to sugarcane increased soil C stocks with an accumulation of 3.5 Mg ha⁻¹ C-CO₂ over 7 years, a trend which reflected the impact 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.

4.4.2 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.

The adoption of green harvesting resulted in increases of the soil C stock in all the conditions simulated when compared with the burning system (Fig 3), in agreement with modeling studies of Vallis et al. (1996); Galdos et al. (2009) and Bortolon et al. (2011) and field measurements of Luca, et al. (2008) and Razafimbelo et al. (2006). Higher C stocks were projected in clay soils within the range of soil textures represented with 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, MIELNICZUK E CERRI, 2009; BAYER et al., 2011). C levels tend to increase with increasing clay content because C is often captured within small pores of clay particles that are then not physically accessible to microbes or bound in the interlayers of silicate clays (PAUL, 1984; LEPSCH; MENK; OLIVEIRA, 1994; LILIENFEIN et al., 1998).

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. Clay soils comprised of the densest native vegetation (regular pastures) and therefore higher initial C stocks showed greater C losses due to considerable differences of SOM inputs and soil perturbation in the sugarcane agroecosystem. As burning is replaced for the green harvesting system the C which would have been emitted to the atmosphere as CO₂ during the burning returns to the soil in the litter thereby avoiding the continuous C loss and contributing to the C maintenance over the time (Fig 4B) in those soils.

Under different conditions of native vegetation (priority and low suitability) the change of harvesting system causes C accumulation over time which can reach values even superior than those predicted for the pastures (Fig 3A) in clay soils, and sugarcane C stocks very close to those predicted in sandy soils pastures (Fig 3 and Fig 4A).

Despite of the higher C stocks in clay soils the projections point out the importance of suppressing burning practice in coarse textured soils, where the residue management increased the soil C stock in almost twice the value found under the baseline (SB).

In terms of annual C stock variation the model indicates C losses ranging from 0.18 to 0.19 Mg ha⁻¹ year⁻¹ in areas of sugarcane expansion classified as “priority suitability, and from 0.17 to 0.43 Mg ha⁻¹ year⁻¹ in “regular suitability” areas due to the sugarcane planting involving pre-harvest burning. Higher values of C depletion in those areas (regular suitability) were observed in Atlantic forest native vegetation locations, where considerable reduction of C inputs due to pre-harvest burning affects the soil C dynamics significantly. Nevertheless, changes in the harvest system allow recovery of more than 80% of the mean C losses.

The addition of organic amendments such as vinasse and filter cake, residues from the industrial sugarcane processing which are typically applied to the soil as a form of cycling organic matter, seems to increase the potential of 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. The combination of mineral and organic fertilization would achieve soil C stocks surpassing the level in the previous management, irrespective of the soil texture (Fig 3 and Fig 4).

In the modelling those organic matter additions (omad.100) supply considerable annual amounts of C and N to the soil favor the litter mineralization and increase the soil C stocks in 0.37 Mg ha⁻¹ year⁻¹ and 0.34 Mg ha⁻¹ year⁻¹ in SC2 and SC3 respectively. These results are consistent with the mean C rate accumulation of 0.23 Mg ha⁻¹ year⁻¹ projected by Galdos et al. (2009) in a modelling study involving Brazilian sugarcane planting. Measured field data have also evidenced the benefits of vinasse addition in increasing the soil organic matter content (CANELLAS et al., 2003; ZOLIN et al., 2011; DE SOUZA BARROS et al., 2013). Brandani et al. (2014) quantified the SOC stocks in a clay soil under sugarcane planting involving both systems: burning and organic amendments which are in the average of the values projected in this study (Fig 4).

Additionally, because of the N content of those residues, the biomass productivity is also projected to increase significantly in all the situations studied. Stalk's yield rises in mean 18 Mg ha⁻¹ from SC1 to SC2 and this parameter is not affected by the reduction of the N inputs (SC3), remaining in a mean 15 Mg ha⁻¹ higher than SC1. Paul and Clark (1989) and Trinsoutrot et al. (2000) reported that organic residues with a C/N ratio below 24 induced net N mineralization which favors the litter decomposition without affecting the soil N content

and consequently the yield of the crop. The impact of vinasse application on the sugarcane yield has been widely documented. A mean rate of increase in the productivity of 26% was observed in previous studies (GÓMEZ; RODRÍGUEZ, 2000; ARMEGOL; LORENZO; FERNÁNDEZ, 2003; DE RESENDE ET AL., 2006; DA SILVA BONO; DE AR PEREIRA, 2014) in agreement with our findings.

In addition to the impact in the productivity, reductions in N fertilization rates due to the organic matter additions can significantly 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 $1.32 \text{ kg ha}^{-1} \text{ N-N}_2\text{O}$ per cycle (4 ratoons) of sugarcane planting.

Conservational management practices in sugarcane involving returning residues to the soil plus organic matter additions would contribute to the long-term recovery of the transient C loss due to the LUC related to the expansion of the crop. The number of years necessary to restore the C stock varies with the texture, native vegetation and the adopted management scenario. Considering just the SC1 the model predicted that after 24 years of conversion to sugarcane the soil C stocks lost can be totally restored in clay and loam soils under priority and regular suitability respectively. Sugarcane involving organic fertilization (SC2 and SC3) allows reducing that payback time to 17 years in clay soils and 18 years in loam soils.

In other textural classes changing the harvest system is not enough to recover the losses of C. According to the modelling estimates the time span is greater in clay soils under regular suitability, whose C stock before the LUC was higher due to the type of native vegetation predominant in those study areas. Recovery the C losses in sandy soils will take a mean time of 24 years for all the suitability classes.

Since the scenarios simulated in this study involved 11-year time span of sugarcane pre-harvest burning, we believe that the impact of LUC in new areas of expansion can be lower if conservational 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 for the soil C debt were performed just considering the soil C dynamics. The production of sugarcane ethanol has an annual GHG equivalent offset of $9.8 \text{ Mg CO}_2 \text{ ha}^{-1}$, which should also be considered in studies of life cycle analysis of this biofuel.

Regarding the trash removal practice, the results obtained in this study pointed out the importance of maintaining sugarcane post-harvest residues on the soil. Removing half of the

trash from the field can decrease the potential C accumulation in the soil by 23% (SC3A); hence affecting the time span of C restoration. The impact of that practice seemed to be higher in clay soils than in sandy soils, where the soil C stocks were greater because of the interaction between clay content and type of native vegetation.

Trash removal by 30% does not drastically affect the soil C storage. A reduction of 13% in the annual C accumulation rate projected for the SC3 was observed in that situation.

Considering the growing interest in the use of sugarcane trash for energetic purposes, the decrease in the C inputs caused by trash removal in SC3A could be offset if changes in the tillage systems are adopted. According to the modelling 1.06 Mg C ha⁻¹ are lost every 5 years due to the conventional tillage of the soil; a value which is consistent with the C losses quantified by Silva-Olaya et al. (2013) in a study performed in a sugarcane field, where the adoption of reduced and minimum tillage decreases the C losses in 85%, favoring the C accumulation.

Our results supported the use of Century model as tool to study the impact of different soil managements in the SOC dynamics in sugarcane. The modelling has shown significant findings to the sugarcane sector in Brazil. 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 results regarding both agronomic and industrial aspects such as N fertilization when organic amendments are performed and trash removal have also been pointed out by the model.

4.5 Conclusion

The Century model was able to reflect the temporal dynamic of soil organic carbon as influenced by the land use change and different sugarcane management practices. According to the modelling, the adoption of conservational practices decrease the number of years that would be needed for the soil C restoration lost due to land-use transition into sugarcane. Reductions in N fertilization rate can be adopted when organic amendments such as vinasse and filter cake are applied in the field providing the plant required nitrogen.

The sub-scenarios simulated indicated that trash removal by 30% does not significantly affect the potential of C accumulation in the soil related to the green harvesting system.

The results obtained generally suggested that the Century model could be an important tool in the definition and development of management strategies which allow C stock increases over time insuring the production of low-carbon renewable fuels.

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5 FINAL CONSIDERATIONS

The main goal of this study was to examine through modelling techniques the soil organic carbon (SOC) dynamics in sugarcane crop in response to the land use change (LUC) caused by expansion and the implementation of different management systems.

A soil data-set collected previously by the research from the “*Laboratório de Biogeoquímica Ambiental*” at CENA-USP allows the parameterization and validation of the Century model, one of the best models in predicting soil organic matter (SOM) dynamics in various ecosystems of temperate and tropical climates.

In order to better understand the impact of land-use transition into sugarcane we performed physical soil C fractionation to soil samples collected in 34 areas forming 17 comparison pairs and representing the three major LUC scenarios. Our results suggested that conversion from native vegetation and pastures to sugarcane causes a C depletion in the labile fraction (POM) as well as in the stabilized pool associated to the mineral fraction (MOM). The losses were higher in the top layer (0 -10 cm depth) where the perturbation is greater because of the sugarcane cultivation.

Conversely, C accumulation in MOM fraction was observed for the transition from annual crops to sugarcane. We could not estimate the impact of this LUC on POM due to differences in the annual cropland management which seems substantially affect the dynamic of this pool. Despite that the results are not conclusive in this regard, they could indicate that the response of that pool to LUC varies as a function of previous management in annual cropland; however more studies have to be done involving this issue.

Field measurements of above and belowground biomass of sugarcane for different ratoon stages allowed for the estimation of shoot:root ratio and net annual carbon inputs to the soil. Subsequently, by using the C conversion ratio (rates of C crop residue transforming into SCO) and the ethanol offset obtained in literature we recalculated payback times for sugarcane biofuel carbon debts to 13 years for Cerrado wooded, 7 years for Cerrado grassland and 6 years for pasture conversions into sugarcane.

Afterwards, upon parameterizing and validating the Century model we verified the impact of different scenarios of management in sugarcane on the SOC dynamics. The potential of C accumulation and restoration time projected by the model of the scenario involving green harvesting, was different than the estimated in chapter three using biometric measurements. For this last approach we calculated the contribution of sugarcane residues in supplying C to

the soil by using the C conversions ratio of 13% reported by Robertson and Thorburn (2007). Further on the modelling study the Century indicated a proportion of C retained in the soil ranging from 6% in sandy soils to 10% in clay soils.

Though both approaches are different the results converged in that more than 30 years would take for the soil C restoration lost due LUC from pastures. A higher time span projected in the simulations could be influenced by a run-time of 11 years involving pre-harvest burning prior to the change to green harvesting, which caused a significant C depletion.

Since no data about C conversion ratio in sugarcane crop different from that calculated by Robertson and Thorburn (2007) was available, the estimates performed involving measured above and belowground inputs were a valuable first approximation of the impact of green harvesting and ethanol offset in the payback time of the C debt.

With the future expansion of sugarcane projected involving mainly pasture areas, the results generated in this research are important tools not only for the public decision makers but also for the sugarcane private sector. Our findings can be used as a scientific base in other studies regarding the sustainability of sugarcane ethanol and also drive decision makers and planners from the agribusiness in the adoption of appropriate measures for the growing and development of sugarcane chain, with the goal of delivering low-carbon renewable fuels.

APPENDIX

Appendix A – Soil texture and time span of sugarcane cultivation in the study areas

County	State	Land use	Soil Texture (SBCS)	Time Span (years)	No burning (years)	Land use Reference	Soil Texture (SBCS)
Ipaussu	SP	Sugarcane	Clayey	16	0	Pasture	Clayey
Andradina	SP	Sugarcane	Medium	12	2	Pasture	Medium
Andradina	SP	Sugarcane	Medium	11	2	Pasture	Medium
Campo Florido	MG	Sugarcane	Medium	5	5	Annual crops	Medium
Campo Florido	MG	Sugarcane	Medium	5	5	Pasture	Medium
Campo Florido	MG	Sugarcane	Sandy	10	5	Pasture	Sandy
Arapora	MG	Sugarcane	Clayey Heavy	40	2	Cerrado	Clayey
Arapora	MG	Sugarcane	clayey	12	3	Pasture	Clayey
Arapora	MG	Sugarcane	Clayey Heavy	8	0	Pasture	Clayey
Arapora	MG	Sugarcane	clayey	9	2	Cerrado	Clayey
Igarapava	SP	Sugarcane	Clayey	10	3	Pasture	Clayey
Igarapava	SP	Sugarcane	Clayey	12	2	Pasture	Medium
Igarapava	SP	Sugarcane	Medium	7	2	Pasture	Medium
Igarapava	SP	Sugarcane	Clayey	17	0	Pasture	Clayey
Igarapava	SP	Sugarcane	Clayey	23	3	Pasture	Clayey
Igarapava	GO	Sugarcane	Clayey	13	9	Pasture Annual crops	Clayey
Iguatemi	MS	Sugarcane	Clayey	15	0		Clayey

Appendix B - Soil dataset used for Century parameterization, validation and long-term simulations

(continues)

County	State	Land use	Sand	Clay	Silt	Bulk density	Time span
			-----g kg ⁻¹ -----			g cm ⁻³	(Years)
Ipaussu	SP	Sugarcane	442	361	197	1.33	16
Ipaussu	SP	Sugarcane	234	580	186	1.14	12
Ipaussu	SP	Sugarcane	270	608	121	1.14	10
Ipaussu	SP	Pasture	297	525	178	1.32	41
Ipaussu	SP	Pasture	175	677	148	1.16	41
Ipaussu	SP	Native Vegetation	155	748	96	0.85	NA
Iacanga	SP	Sugarcane	854	115	31	1.64	16
Iacanga	SP	Sugarcane	855	103	42	1.63	9
Iacanga	SP	Sugarcane	836	126	38	1.56	11
Iacanga	SP	Pasture	302	220	765	1.59	51
Iacanga	SP	Native Vegetation	882	17	101	1.39	NA
Itirapina	SP	Sugarcane	765	128	108	1.49	7
Itirapina	SP	Sugarcane	789	138	73	1.58	23
Itirapina	SP	Pasture	809	117	73	1.60	41
Anhembi	SP	Sugarcane	929	45	26	1.61	8
Anhembi	SP	Sugarcane	930	42	29	1.60	13
Anhembi	SP	Sugarcane	910	65	24	1.48	18
Anhembi	SP	Sugarcane	873	88	39	1.64	17
Anhembi	SP	Sugarcane	818	157	25	1.54	17
Anhembi	SP	Sugarcane	833	127	40	1.64	22
Anhembi	SP	Pasture	904	75	20	1.58	41
Anhembi	SP	Pasture	914	60	26	1.59	41
Anhembi	SP	Pasture	832	131	38	1.61	41
Anhembi	SP	Pasture	790	115	95	1.60	26
Igarapava	SP	Sugarcane	265	477	258	1.10	10
Igarapava	SP	Sugarcane	395	378	227	1.10	12
Igarapava	SP	Sugarcane	407	388	206	1.12	7
Igarapava	SP	Sugarcane	780	105	115	1.62	7
Igarapava	SP	Sugarcane	164	504	332	1.04	17
Igarapava	SP	Sugarcane	330	462	208	1.15	23
Igarapava	SP	Sugarcane	687	216	97	1.35	7
Igarapava	SP	Sugarcane	252	314	434	1.05	18
Igarapava	SP	Pasture	324	476	200	1.22	51
Igarapava	SP	Pasture	674	191	135	1.43	41
Igarapava	SP	Pasture	562	318	120	1.38	41
Andradina	SP	Sugarcane	736	181	84	1.72	6
Andradina	SP	Sugarcane	816	138	46	1.53	12

Appendix B - Soil dataset used for Century parameterization, validation and long-term simulations

(continuation)

County	State	Land use	Sand	Clay	Silt	Bulk density g cm ⁻³	Time span (Years)
			-----g kg ⁻¹ -----				
Andradina	SP	Sugarcane	794	125	81	1.70	11
Andradina	SP	Pasture	746	185	69	1.56	41
Andradina	SP	Pasture	750	167	83	1.61	41
Andradina	SP	Pasture	792	121	87	1.61	41
Andradina	SP	Pasture	817	125	58	1.52	41
Aracatuba	SP	Sugarcane	763	125	112	1.53	31
Aracatuba	SP	Sugarcane	796	138	66	1.56	9
Aracatuba	SP	Sugarcane	813	100	86	1.62	31
Aracatuba	SP	Sugarcane	856	67	77	1.79	31
Aracatuba	SP	Pasture	734	156	109	1.62	41
Campo Florido	MG	Sugarcane	595	297	108	1.50	5
Campo Florido	MG	Sugarcane	786	151	63	1.58	5
Campo Florido	MG	Sugarcane	834	88	78	1.59	8
Campo Florido	MG	Sugarcane	809	111	80	1.49	10
Campo Florido	MG	Sugarcane	791	76	133	1.46	10
Campo Florido	MG	Sugarcane	784	119	97	1.48	8
Campo Florido	MG	Sugarcane	741	176	83	1.55	9
Campo Florido	MG	Agriculture	717	210	72	1.48	22
Campo Florido	MG	Pasture	781	163	56	1.51	51
Campo Florido	MG	Pasture	814	96	89	1.55	51
Campo Florido	MG	Pasture	810	109	81	1.56	51
Campo Florido	MG	Sugarcane	802	132	66	1.46	6
Arapora	MG	Sugarcane	408	455	138	1.22	10
Arapora	MG	Sugarcane	258	630	112	1.10	19
Arapora	MG	Sugarcane	193	435	372	1.04	40
Arapora	MG	Sugarcane	142	554	304	1.08	12
Arapora	MG	Sugarcane	132	625	244	1.06	22
Arapora	MG	Native vegetation	172	647	182	1.07	NA
Arapora	MG	Sugarcane	196	623	181	1.02	4
Arapora	MG	Sugarcane	171	442	387	1.00	8
Arapora	MG	Sugarcane	198	581	221	1.01	4
Arapora	MG	Sugarcane	161	619	220	1.12	9
Arapora	MG	Sugarcane	210	606	185	1.23	13
Arapora	MG	Sugarcane	235	594	170	1.02	8
Arapora	MG	Sugarcane	240	546	214	1.07	18
Arapora	MG	Sugarcane	253	533	214	0.98	16
Arapora	MG	Sugarcane	182	561	257	1.14	17
Arapora	MG	Sugarcane	152	599	249	1.08	5
Arapora	MG	Sugarcane	94	520	386	0.90	9

Appendix B - Soil dataset used for Century parameterization, validation and long-term simulations

(conclusion)

County	State	Land use	Sand	Clay	Silt	Bulk density	Time span
			-----g kg ⁻¹ -----			g cm ⁻³	(Years)
Arapora	MG	Pasture	265	611	124	1.01	41
Arapora	MG	Native vegetation	196	375	429	0.92	41
Arapora	MG	Pasture	152	571	277	1.12	36
Arapora	MG	Pasture	216	584	200	1.04	41
Arapora	MG	Pasture	213	572	215	1.01	46
Arapora	MG	Pasture	248	444	308	0.96	31
Arapora	MG	Pasture	165	582	254	1.10	41
Arapora	MG	Pasture	220	597	182	1.09	46
Arapora	MG	Native vegetation	284	575	141	0.98	NA
Arapora	MG	Pasture	262	503	235	1.18	46
Arapora	MG	Pasture	277	536	186	1.04	46
Arapora	MG	Pasture	200	566	234	1.09	46
Arapora	MG	Native vegetation	190	513	297	0.92	NA
Arapora	MG	Agriculture	94	589	318	1.03	35
Goiatuba	GO	Sugarcane	270	398	332	1.11	13
Goiatuba	GO	Sugarcane	503	354	143	1.26	22
Goiatuba	GO	Sugarcane	388	374	238	1.03	21
Goiatuba	GO	Sugarcane	502	409	88	1.04	18
Goiatuba	GO	Sugarcane	297	472	231	0.99	15
Goiatuba	GO	Pasture	266	521	213	0.89	41
Goiatuba	GO	Pasture	433	396	171	1.12	41
Goiatuba	GO	Native vegetation	565	313	122	1.25	NA
Goiatuba	GO	Pasture	344	436	220	0.81	41
Maracaju	MS	Sugarcane	427	365	208	1.37	4
Maracaju	MS	Sugarcane	228	587	185	1.14	2
Maracaju	MS	Native veg	289	446	285	1.14	NA
Maracaju	MS	Sugarcane	305	480	215	1.30	4
Maracaju	MS	Agriculture	270	548	182	1.28	31
Maracaju	MS	Agriculture	275	499	226	1.30	18
Maracaju	MS	Agriculture	303	452	245	1.29	18