SÃO PAULO STATE UNIVERSITY – UNESP
JABOTICABAL CAMPUS

GREENHOUSE GAS BALANCE ASSOCIATED WITH SUGARCANE PRODUCTION IN SOUTH-CENTRAL BRAZIL, CONSIDERING THE MANAGEMENT AND EXPANSION

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AUTHOR'S CURRICULUM DATA

RICARDO DE OLIVEIRA BORDONAL – Son of José Orlando Bordonal and Teresa Cristina de Oliveira Bordonal, he was born on September 22, 1986, in Orlândia, São Paulo state, Brazil. From 2005 to 2009, he attended São Paulo State University (UNESP) – College of Agricultural and Veterinarian Sciences (FCAV) – Jaboticabal campus, and graduated in Agronomy. In August 2010, he entered the M.Sc. program at UNESP/FCAV, and in 2012 received a M.Sc. degree in Agronomy (Crop Production). Ricardo also holds a Specialist's degree (2012) in Environmental Management from the Federal University of São Carlos (UFSCAR). His expertise is associated with environmental and agricultural sciences, especially on the following research topics: sugarcane management, climate change, inventory, greenhouse gas emission, mitigation, soil use and management, bioenergy, sustainability, and soil CO_2 emission. In August 2012, he joined the Ph.D. program at UNESP/FCAV, working on the topic "Greenhouse gas balance associated with sugarcane production in south-central Brazil, considering the management and expansion". During this period, Ricardo also conducted part of his doctoral research as a visiting graduate student at The Ohio State University. In February 2016, he submitted the doctoral thesis to an examination panel, and received his Ph.D. degree in Agronomy (Crop Production) at UNESP/FCAV.

If you can’t fly then run, if you can’t run then walk, if you can’t walk then crawl,
but whatever you do you have to keep moving forward.

Martin Luther King Jr.

I DEDICATE

To God for blessing me with health, and encouraging me to achieve my goals throughout life.

To my beloved parents, José Orlando and Teresa Cristina, my greatest example in life. **This is for you!**

I OFFER

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SUMMARY

GREENHOUSE GAS BALANCE ASSOCIATED WITH SUGARCANE PRODUCTION IN SOUTH-CENTRAL BRAZIL, CONSIDERING THE MANAGEMENT AND EXPANSION

ABSTRACT – The substitution of fossil fuel with sugarcane ethanol aiming to reduce emissions of greenhouse gases (GHGs) has recently been debated because of the possible emissions incurred from land use change (LUC). This work was based on GHG inventory from cultivation and LUC of recently established sugarcane plantation in south-central Brazil, with the purpose of estimating the impact of expansion on GHG balance, including emissions and removals due to LUC. Changes in quantity and quality of soil carbon (C) upon conversion of diverse agricultural systems (coffee, citrus, annual crops and pasture) to sugarcane in southern Brazil were also assessed through field experiments. The estimates show that sugarcane cultivation and its expansion during 2006-2011 in south-central Brazil presented an overall accumulated GHG balance of 217.1 Tg CO_2eq by 2030, including emissions from cultivation activities and emissions/removals due to LUC. Expansion of sugarcane plantation contributed to attenuate part of GHG emissions from agricultural production phase. Similarly, the ethanol C offset by displacing fossil fuels could readily payback that C deficit. The data obtained by field experiments show that the LUC of coffee and citrus to sugarcane depleted soil C stock by 21.5% (26.8 Mg C ha^{-1}) and 23.6% (34.9 Mg C ha^{-1}) in the 0-100 cm layer after a period of 3 and 4 years, respectively. In contrast, there was no significant difference in soil C stocks in 0-100 cm depth upon conversion of pasture and annual crop into sugarcane. However, only the conversion of pasture into sugarcane decreased soil C stock in 0-20 cm depth, with depletion of 13.3 Mg C ha^{-1} (43.9%) over 8 years after the LUC. With regard to the quality of soil C, the data of Laser-Induced Fluorescence Spectroscopy (LIFS) showed that the higher the losses of soil C, the greater was the humification index (H_{LIFS}) of soil organic matter (SOM). In general, conversion of the agrosystems (e.g., coffee, citrus, annual crop and pasture) into sugarcane increased H_{LIFS} of SOM. For some depths, H_{LIFS} more than doubled in comparison with the previous land uses. We expect that the results achieved in this work may contribute to the development of actions and public policies to strengthen strategies for GHG mitigation and ensure the environmental benefits of sugarcane ethanol in Brazil.

Keywords: ethanol production, inventory, land use change, mitigation, sugarcane management, climate change

BALANÇO DE GASES DE EFEITO ESTUFA ASSOCIADO À PRODUÇÃO DE CANA-DE-AÇÚCAR NO CENTRO-SUL DO BRASIL, CONSIDERANDO-SE O MANEJO E A EXPANSÃO

RESUMO – A substituição dos combustíveis fósseis pelo etanol de cana-de-açúcar visando à redução das emissões de gases de efeito estufa (GEE) tem sido recentemente questionada devido às possíveis emissões decorrentes da mudança do uso da terra (MUT). Este trabalho se baseou no inventário de GEE do cultivo e da MUT associada à expansão da cana-de-açúcar no centro-sul do Brasil, com a finalidade de estimar o impacto dessa expansão no balanço de GEE, incluindo as emissões e remoções devido à MUT. Objetivou-se também, por meio de experimento de campo, avaliar as mudanças na quantidade e qualidade do carbono (C) do solo após a conversão de diferentes agrossistemas (café, citros, cultura anual e pastagem) para cana-de-açúcar no sudeste do Brasil. As estimativas apontam que o cultivo da cana-de-açúcar e sua expansão durante 2006-2011 no centro-sul do Brasil resultaram no balanço acumulado total de GEE de 217,1 Tg CO_2eq em 2030, incluindo as emissões das atividades de cultivo e as emissões/remoções associadas à MUT. As estimativas indicam que a expansão dos canaviais contribuiu para atenuar parte das emissões de GEE da fase de produção agrícola. Do mesmo modo, o uso de etanol em substituição aos combustíveis fósseis poderia facilmente compensar esse déficit de C. Os resultados das avaliações de campo apontam que a conversão de café para cana-de-açúcar resultou na depleção dos estoques de C do solo de 21,5% (26.8 Mg C ha^{-1}) e 23,6% (34.9 Mg C ha^{-1}) na camada de 0-100 cm ao longo dos períodos de 3 e 4 anos após a MUT, respectivamente. As conversões de pastagem e cultura anual para cana-de-açúcar não apresentaram diferenças significativas na camada de 0-100 cm. Entretanto, apenas a transição de pastagem para cana apresentou diferenças significativas na camada de 0-20 cm, resultando na depleção dos estoques de C do solo de 43,9% (13.3 Mg C ha^{-1}) durante 8 anos após a conversão. Com relação à qualidade do C do solo, a técnica de espectroscopia de fluorescência induzida por laser mostrou que quanto maior a perda de C no solo devido à MUT para cana, maior o índice de humificação (H_{FIL}) da matéria orgânica do solo (MOS). Em geral, a conversão dos agrossistemas (café, citros, cultura anual e pastagem) para cana-de-açúcar promoveu o aumento do H_{FIL} da MOS. Em algumas profundidades, o H_{FIL} mais do que dobrou em relação aos usos anteriores. Espera-se que os resultados gerados neste trabalho contribuam para o desenvolvimento de ações e políticas públicas visando fortalecer estratégias que possam potencializar ainda mais a mitigação de GEE, e garantir os benefícios ambientais do etanol de cana-de-açúcar no Brasil.

Palavras-chave: produção de etanol, inventário, mudança do uso da terra, mitigação, manejo da cana-de-açúcar, mudanças climáticas.

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CHAPTER 1 – GENERAL CONSIDERATIONS

1.1 Introduction and Justification

1.1.1 On the agriculture and climate change

Economic and population growth have driven a large strain for land and other natural resources to produce food, fiber and energy (TILMAN et al., 2009). The atmospheric concentration of the greenhouse gases (GHG) has increased since 1750, mostly due to human activity. In 2011, the concentrations of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) were 391 ppm, 1803 ppb, and 324 ppb, and exceeded the pre-industrial levels by about 40%, 150%, and 20%, respectively (IPCC, 2013).

The additional greenhouse effect has been largely driven by the burning of fossil fuels since the mid-20th century. Likewise, agriculture directly contributes with 14% of global anthropogenic GHG emissions and accounts for an additional emission of 17% when the conversion of land-use to agricultural production is taken into account (LYBBERT; SUMNER, 2012). The increased concentration of anthropogenic greenhouse gas (GHG) is reported as a causal link between external drivers of climate change and observed changes in climatic variables (e.g., precipitation intensity, cyclones, floods and droughts; IPCC, 2013).

Beyond of its contribution to climate change, agriculture is also affected by those impacts, with projections of additional risks for food security in the near future (SCHMIDHUBER; TUBIELLO, 2007). The effects of climate change on tropical agriculture could lead to decreased productivity and quality of agricultural goods, changes in crop management and reduction of areas suitable for agricultural production, with social, economic and political consequences (CERRI et al., 2007a).

Unfavorable climatic conditions over the last few years are among several other aspects that have affected sugarcane plantations (*Saccharum officinarum*) with regard to productivity declines in different regions of Brazil (CONAB, 2014), dropping from 115 ton ha^{-1} in 2008 to 69 ton ha^{-1} in 2012 (ANGELO, 2012). Simulations presented by ASSAD et al. (2004) indicate that the increased temperature over the next years can result in a reduction of areas suitable for agricultural production in Brazil on more than 95% in the states of Goiás, Minas Gerais and São Paulo, and about 75% in Paraná.

Unlike the developed countries, climate change issues in Brazil are mostly related to land use and land-use change (LUC) as approximately 80% of the national GHG emissions in 2005 were sourced from agriculture and LUC sectors (MCT, 2010). However, public policies and interventions in beef and soy supply chains have already contributed for the recent 70% decline in deforestation in the Brazilian Amazonia, and this target may reach to a 90% reduction in 2018 (NEPSTAD et al., 2014). Even holding the largest potential for agricultural expansion in the coming years, Brazil has achieved impressive results in reducing GHG emissions by 40% since 2005 through the reduction of deforestation rates in the Brazilian Amazonia (LAPOLA et al., 2013).

The characterization of how the changes on the soil use and management affects the dynamics of GHG emissions over time is something of great importance, especially in tropical regions, to determine the impact of LUC on global climate. Soils account for around 1,550 Pg of organic carbon (C), more than twice the amount of C present in the atmosphere (720 Pg) and about three times more than the C of the terrestrial biota (LAL, 2001; FOLLETT, 2001).

Greenhouse gas fluxes in agriculture are complex and heterogeneous, but management practices in agricultural systems could offer mitigation opportunities. Moreover, practices that reduce the GHG emission at the same time they enhanced the adaptive capacity of agricultural systems to climate change. This would increase agricultural yields and lead to increased food security (HARVEY et al., 2014).

The global technical potential for mitigation options in agriculture by 2030, considering all gases, was estimated to be ~5500-6000 $MtCO_2$-eq year^{-1} (SMITH et al., 2008). Of the technical potential ("*high agreement, much evidence*") estimated by SMITH et al. (2008), about 89% is from restoring soil carbon (soil C sequestration), about 9% from mitigation of CH_4 and about 2% from mitigation of soil N_2O emissions.

Limiting climate change will require substantial and sustained reductions of GHG emissions. Some options to mitigate climate change in agricultural areas include: improved management of agricultural lands; improved pasture management, restoration of cultivated organic soils; recovery of degraded lands, management of livestock, manure/biosolid management and bioenergy production (IPCC, 2007). SMITH et al. (2008) estimated a global potential mitigation of 770 $MtCO_2$-eq $year^{-1}$ by 2030 from improved energy efficiency in agriculture (e.g., through reduced fossil fuel use).

As soil is the compartment where C is more concentrated in the terrestrial environment, and it is prone to LUC (CERRI et al., 2007b; MAIA et al., 2010), global initiatives have arisen aiming to investigate the effects of LUC and its results in terms of GHG balance, considering emissions and sequestration (MILNE et al., 2007). Moreover, changes in management practices in the sugarcane cultivation have been considered as important as to the current expansion of the agricultural frontier (CERRI et al., 2007b), since large areas are being converted from a burned harvest regime to a non-burned green mechanized harvest in south-central Brazil.

1.1.2 Inventory of greenhouse gas emissions in agricultural areas

Awareness of environmental issues in the medium and long term is essential for sustainable development. It is necessary to develop a set of strategies that include adaptation, mitigation, and new researches to mitigate climate change. The United Nations Framework Convention on Climate Change (UNFCCC) is the main multilateral forum focused on addressing climate change. Guided by the uncertainties of the future and a strong concern on global climate, a common and differentiated commitment has been established among all members, such as the reduction and stabilization of GHG concentrations in order to ensure the food security and economic development by limiting warming over the 21st century to below 2°C relative to pre-industrial levels.

In the Intended Nationally Determined Contribution (INDC) recently published by Brazilian government, and submitted to the UNFCCC under the Conference of the Parties in Paris (COP21), Brazil has pledged to reduce GHG emissions by 43% below 2005 levels in 2030 and adopt further measures with a 2°C-increase temperature goal, in particular to restore and reforest 12 million hectares of forest by 2030 and strengthen policies and measures to achieve zero illegal deforestation by 2030 in the Brazilian Amazonia (UNFCCC, 2015).

Government requirements for mitigation and adaptation to climate change resulted in methodologies as the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). This is an important tool for estimating national inventories of anthropogenic emissions by sources and removals by sinks of GHG, assisting parties in fulfilling their commitments under the UNFCCC. Such methodology is also important for quantifying and analyzing the potential impacts in terms of GHG balance associated with agricultural production, aiming to guide the formulation of public policies.

The determination of the potential GHG mitigation and the effective substitution of fossil fuels using sugarcane ethanol should be supported by studies of environmental impacts, particularly by methodologies aimed at analyzing the GHG balance and consumption of fossil energy in different production systems. Studies of GHG inventories are adequate in this context as they allow a comprehensive analysis of the entire production chain.

The quantification of GHG emission from sugarcane ethanol has been triggered by the need of new studies in the scientific community. Several have demonstrated the strategic advantages of sugarcane ethanol for mitigating GHG compared to other bioenergy crops in substitution of fossil fuels (NGUYEN et al., 2007; RENOUF et al., 2008; BÖRJESSON, 2009; GOLDEMBERG; GUARDABASSI, 2010). However, the rapid changes in both industrial and agricultural sectors continue to raise debate and require further analysis and discussion.

For instance, legal restrictions regarding the sugarcane pre-harvest burning, and the consequent increase of mechanical harvesting without burning could influence the GHG balance in agricultural areas in various forms, since the quantities of diesel and agricultural inputs (nitrogen fertilizer, vinasse, filter cake, limestone and pesticide) consumed in the crop production vary according to the management system adopted, namely with or without the burning practice.

BORDONAL et al. (2012) reported that the conversion from a burnt to an unburnt sugarcane harvesting system, including the adoption of recommended management practices (e.g., reduced soil tillage and crop rotation with N-fixing crops during sugarcane field renovation), could save from 1223.6 to 1587.3 kg CO_2eq ha^{-1} $year^{-1}$. In São Paulo state, GHG emissions from harvesting operations in sugarcane fields have decreased by approximately 37.6% over the last 20 years, from 1.015 ton CO_2eq ha^{-1} in 1990 to 0.633 ton CO_2eq ha^{-1} in 2009 (CAPAZ et al., 2013). Government actions are already becoming effective for reducing sugarcane straw burning (FRANÇA et al., 2014).

1.1.3 Sugarcane ethanol and the potential for greenhouse gas mitigation

Increases in energy supply from solar, wind, hydraulic and bioenergy sources have been enhanced by the growing concern on GHG emissions from fossil fuels, depletion of petroleum reserves, and risks of climate change and extreme events (LAL, 2014). Biofuels are one of the few technologies that may result in negative GHGs emissions through replacement of fossil fuels, and a reduction of up 85% has been reported for sugarcane-based ethanol (BÖRJESSON, 2009). In addition, they are widely propounded by presenting potential benefits such as restoring degraded soils, increasing both C budgets in soil and biomass, and also cooling the local climate (LOARIE et al., 2011; LAL, 2014).

Brazil already has one of the largest and most successful biofuel programs to date, including cogeneration of electricity using biomass. The sugarcane production is mostly concentrated in the south-central region of Brazil, accounting for about 90% of the total cultivated area in 2015. São Paulo is the state with the largest expansion of sugarcane plantation during the last years, holding around 60% of the cultivated area in south-central Brazil (UNICA, 2015).

The Brazilian Alcohol Program (*Proálcool*) was launched in 1975 aiming to reduce the reliance on oil imports through production of sugarcane-based ethanol, and the environmental benefits were soon recognized by presenting an avoided emission of 27.5 Tg CO_2equivalent in 2003 due to substitution of gasoline use in Brazil (MACEDO, 2005). On a global scale, Brazil is the second largest producer of ethanol and represents nearly 33% of the worldwide production, which could play an important role in supplying future ethanol needs (CERQUEIRA LEITE et al., 2009).

Several food crops are used for biofuels production, including grains (maize, sorghum and wheat), sugar crops (sugarcane, sugar beet), starch crops (cassava), and oilseed crops (soybean and oil palm). Nevertheless, the GHG savings achieved by biofuels are strongly reliant on the feedstock alternative considered and the management practices associated to its agricultural production (DAVIS et al., 2013). Recent analysis of the energy balance and GHGs emissions from alternative options of biofuels started a major controversy and discussions about the true outcomes related to its sustainability (MACEDO et al., 2008; RENOUF et al., 2008; SEABRA et al., 2011; TSAO et al., 2011; DUNN et al., 2013).

Certain basic issues on the expansion of biofuels remain under debate worldwide, especially regarding the land requirements to supply the future demand of ethanol (LEAL et al., 2013). Ethanol production from corn and sugarcane is expected to increase from 80 to approximately 200 billion liters in 2021 (GOLDEMBERG et al., 2014). In order to achieve this target in an environmentally sound manner, several aspects regarding the production of sugarcane ethanol must be assessed, i.e., land use change (FARGIONE et al., 2008; LAPOLA et al., 2010; MELLO et al., 2014), air quality (TSAO et al., 2011), GHG balance associated with sugarcane cultivation (BORDONAL et al., 2012), farm inputs (LAL, 2004) and, the energy balance and C footprint (LAL, 2014).

There is a growing need for all productive sectors to develop GHG mitigation techniques to combat global warming. Inventorying the potential for GHG mitigation in sugarcane fields in southern Brazil, BORDONAL et al. (2013) estimated that changes in management practices during the sugarcane cultivation, such as the conversion of harvest system from a burnt to an unburnt regime and the reduced soil tillage in addition to the introduction of an N-fixing crop during crop renovation, if adopted, could result in GHG mitigation potentials ranging from 50.5 to 70.9 Mt CO_2eq over the period from 2012 to 2050 (Figure 1). Therefore, the adoption of management practices that lead to a reduction of GHG emissions in sugarcane areas could contribute considerably to achieving the objectives set by Brazilian government to curb emissions, in addition to promoting sustainable production of sugar and ethanol in Brazil.

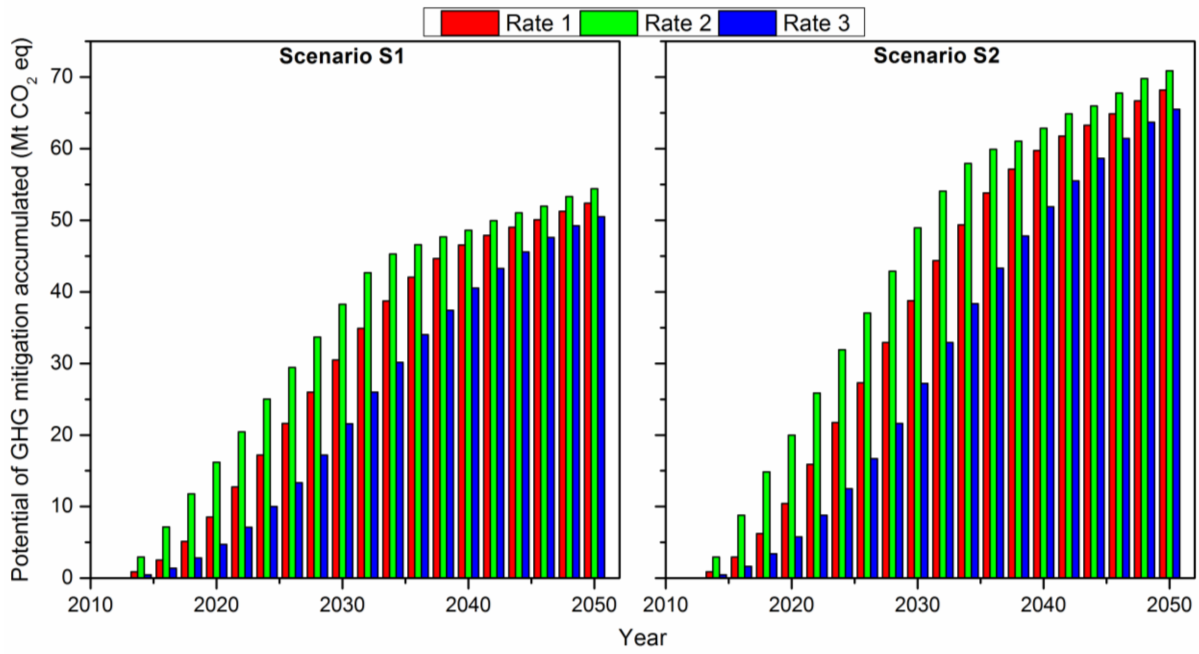

Figure 1. Avoided greenhouse gas emissions (in Mton CO_2equivalent) from 2012 to 2050 due to the conversion of remaining sugarcane areas harvested with burning (2011 harvest season – 1,670,521 ha) to green harvest scenarios in São Paulo State – Brazil, S1 (conventional soil tillage) or S2 (reduced soil tillage and crop rotation), based on three conversion rates (red bar based on State Law – rate 1; green bar based on Protocol – rate 2; and blue bar based on real data observed – rate 3). Source: BORDONAL et al. (2013).

However, concerns regarding the extent to what the expansion of sugarcane plantation have caused deforestation and/or displacement of food crops arise questions about its sustainability (NGUYEN et al., 2010; WALTER et al., 2011). Energy crops have expanded significantly in Brazil. Between 2005 and 2010 about 4 million hectares of sugarcane were incorporated into the existing cultivated areas in south-central Brazil (ADAMI et al., 2012), totaling 9.6 million hectares cultivated in 2015 (UNICA, 2015). Such expansion has turned the sugarcane as the main source of renewable energy in Brazil, accounting for 15.7% of the domestic energy supply in 2014 (BRASIL, 2015).

The LUC due to agricultural expansion can result in GHG emissions, mainly CO_2. Such emissions derive from the burning of native vegetation, decomposition of plant material and oxidation of soil organic matter (CERRI et al., 2007b; FEARNSIDE et al., 2009). This is due to the change of organic material input in the production system, and can be altered in a negative way, with a reduction of carbon stocks, or positively, with an increase of carbon stocks (MAIA et al., 2010).

GHGs emissions from LUC may be significant depending on how biofuels are produced (SEARCHINGER et al., 2008), so that the carbon savings from sugarcane ethanol could be negated by any pressure of the production expansion over native forests or grasslands (LAPOLA et al., 2010). The soil C debt associated with the conversion from native vegetation and pastoral lands to sugarcane plantation has a payback time of 8 and 2-3 years, respectively (MELLO et al., 2014). Additionally, FARGIONE et al. (2008) reported that the conversion from Cerrado wooded to sugarcane plantation in Brazil releases ~165 Mg CO_2 ha^{-1} over 50 years and requires 17 years to repay the "carbon debt".

Conversely, the replacement of marginal or degraded lands by sugarcane plantation can offset some anthropogenic emissions by recycling atmospheric CO_2 (LAL, 2014). Sugarcane plantation has a potential to store from 15.9 to 29.2 Mg C ha^{-1} yr^{-1} into biomass (BEEHARRY, 2001; RONQUIM, 2007), and the replacement of ecosystems with the lowest C stocks (e.g., degraded grasslands) by energy crops with higher yields (e.g., sugarcane and oil palm), may reduce or even eliminate the payback time of the C debt incurred from LUC (GIBBS et al., 2008).

The magnitude of changes in both C reservoirs (e.g., biomass and soil) following LUC can directly affect the GHG balance associated with sugarcane cultivation and is relevant for assessing the C savings from sugarcane ethanol use in substitution of fossil fuels. Remote sensing satellite images are an effective tool in monitoring the management and expansion of sugarcane plantation (RUDORFF et al., 2010; AGUIAR et al., 2011; ADAMI et al., 2012), allowing the generation of accurate information that can serve as a basis for studies on GHG balance.

Since 2006, the National Institute for Space Research (Instituto Nacional de Pesquisas Espaciais; INPE) monitors the direct land use change (dLUC) associated with sugarcane expansion and delineates areas under sugarcane cultivated with specific management and harvest practices (e.g., manual harvest with prior burning vs. green mechanized harvest without burning) in south-central Brazil.

In this context, there are consolidated methodologies to assess the impact of dLUC and sugarcane cultivation in terms of GHG balance, as proposed by the

"Intergovernmental Panel on Climate Change - IPCC (2006)". This methodology entitled "IPCC Guidelines for National Greenhouse Gas Inventories" allows determining GHG emissions from agricultural production, and losses or gains of C stocks in biomass (above- and below-ground) and soil following the dLUC.

1.2 General goals

The objectives of this work were: (i) to estimate the greenhouse gas balance from cultivation and direct land use change of recently expanded sugarcane plantation in south-central Brazil (Chapter 2); and (ii) to assess the changes in quantity and quality of soil carbon due to the main land-use conversions to sugarcane plantation in southern Brazil (Chapter 3).

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CHAPTER 2 – GREENHOUSE GAS BALANCE FROM CULTIVATION AND DIRECT LAND USE CHANGE OF RECENTLY ESTABLISHED SUGARCANE (*Saccharum officinarum*) PLANTATION IN SOUTH-CENTRAL BRAZIL

Abstract – Inventorying greenhouse gas (GHG) balance associated to sugarcane (*Saccharum officinarum*) based ethanol is critical to assess the degree of carbon (C) neutrality of biofuels. Few studies have considered the GHG emissions from sugarcane cultivation while taking direct land use change (dLUC) into account. This study was conducted to enhance scientific understanding of the GHG balance related to sugarcane cultivation while considering dynamics of all C pools (biomass and soil) upon conversion of diverse land uses into sugarcane during 2006-2011 in south-central Brazil. Based on a comprehensive evaluation of survey data and given that the sugarcane cultivation and dLUC can be credibly assessed by using remote sensing satellite images, estimations of GHG emissions were performed using the IPCC methodologies and expressed in terms of Tg CO_2eq (Teragram = 10^{12} g = 1 million Mg) considering a 20-year time horizon. The overall accumulated GHG balance was 217.1 Tg CO_2eq by 2030, with an emission of 481.6 Tg CO_2eq from sugarcane cultivation being offset by a biomass C sink of -274.5 Tg CO_2eq. Soils had an almost neutral C budget with a slight emission of 10.0 Tg CO_2eq by 2030. Nevertheless, the ethanol C offset by displacing fossil fuels could readily payback that C deficit and ensures the environmental benefits of sugarcane ethanol. Our results show an increase of C reservoirs (biomass and soil) through conversion of arable and pastoral lands into sugarcane, and a decrease of C reservoirs when citrus, plantation forest and natural forest are converted to sugarcane. Here we support that the impact of dLUC on biomass and soil C pools must be considered while expanding sugarcane plantation as an important mechanism for GHG abatement beyond the avoided emissions through use of sugarcane ethanol.

Keywords: ethanol production, bioenergy, C offset, inventory, sugarcane harvest, sugarcane expansion, sustainability, climate change.

2.1 Introduction

Earth's climate is being perturbed by increasing emissions of greenhouse gases (GHG) from fossil fuel combustion and land use change by anthropogenic activities and growing population [1]. Options to simultaneously reduce GHG emissions and mitigate climate change include renewable energy sources as alternative to fossil fuels. In Brazil, sugarcane (*Saccharum officinarum*) derived ethanol can reduce GHG emissions by 85% in relation to fossil fuel [2]. It is also more effective in GHG reductions compared to other feedstock, i.e. corn (*Zea mays* L.), sweet sorghum (*Sorghum bicolor* L. Moench) or sugar beet (*Beta vulgaris*) [3].

Ethanol production in the United States and Brazil represents ~90% of the global production [4]. Brazil is the world's largest sugarcane producer, with a cultivated area in the 2013/2014 at ~9.5 million hectare (Mha) mostly in the south-central region [5]. Sugarcane plantations in Brazil have environmental benefits through direct land use change (dLUC) mainly from pasture or other agricultural crops to sugarcane leading to local climate cooling [6].

Rapidly increasing global trade of ethanol is expanding the area under sugarcane, and raising concerns about its environmental impacts [7]. Any environmental benefits of biofuels by reducing GHG emissions depend on how they are produced. Significant GHG emissions can result from sugarcane production and dLUC [8]. For example, the pre-harvest burning of sugarcane residues is widely practiced, and exacerbates GHG emissions up to 941 kg CO_2eq ha^{-1} yr^{-1} [9].

Among several studies [9-12] conducted on gaseous emission from sugarcane cultivation, only a few have assessed the impact of dLUC. Soils and plant biomass are the two major biologically active terrestrial carbon (C) reservoirs, both containing approximately 2.7 times more C than that in the atmosphere [8]. Thus, small changes in those C pools could have a large impact on GHG emissions savings achieved by the ethanol production in Brazil.

Assessing the effect of dLUC on soil organic carbon (SOC) through conversion of native vegetation, pasture and annual cropland into sugarcane, Mello et al. [13] observed a payback time for the soil C debt of 8 years for native vegetation and 2–3 years for pastures. Yet, conversion to sugarcane plantation can synthesize a large amount of atmospheric CO_2 into biomass, and reducing GHG emissions through dLUC. Ronquim [14] reported a C fixation into biomass of 129 Tg CO_2 due to sugarcane expansion during 1988–2003 in the Sao Paulo state, Brazil. Therefore, the GHG balance of sugarcane ethanol depends not only on GHG emissions associated with feedstock production, but also on the changes in C reservoirs following dLUC [15].

Given that the status of sugarcane cultivation and dLUC can be credibly assessed by using remote sensing satellite images [16-18], the objective of this study was to enhance scientific understanding on the GHG balance related to sugarcane cultivation and its expansion during 2006–2011 in south-central Brazil. Our hypothesis is that changes in biomass and soil C reservoirs through conversion of diverse land uses into sugarcane could help to offset GHG emissions from sugarcane production in addition to the avoided emissions by replacing fossil fuels in Brazil.

2.2 Material and Methods

Brazilian ethanol is produced from sugarcane, and the present assessment comprises of the GHG balance associated with dLUC and sugarcane cultivation in the most intensively cultivated regions in Goias (GO), Mato Grosso (MT), Mato Grosso do Sul (MS), Minas Gerais (MG), Parana (PR) and Sao Paulo (SP). These regions represent ~90% of the total cultivated area (Figure 1) [19]. The methodologies from Intergovernmental Panel on Climate Change (IPCC) were applied to estimate GHG balance from dLUC [20] and sugarcane cultivation [21]. The data were expressed in terms of carbon dioxide equivalent (CO_2eq) according to the global warming potentials of 1, 25 and 298 for carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), respectively [22]. In addition, molar ratio of 1 C = 44/12 CO_2eq was used to convert C mass in CO_2eq.

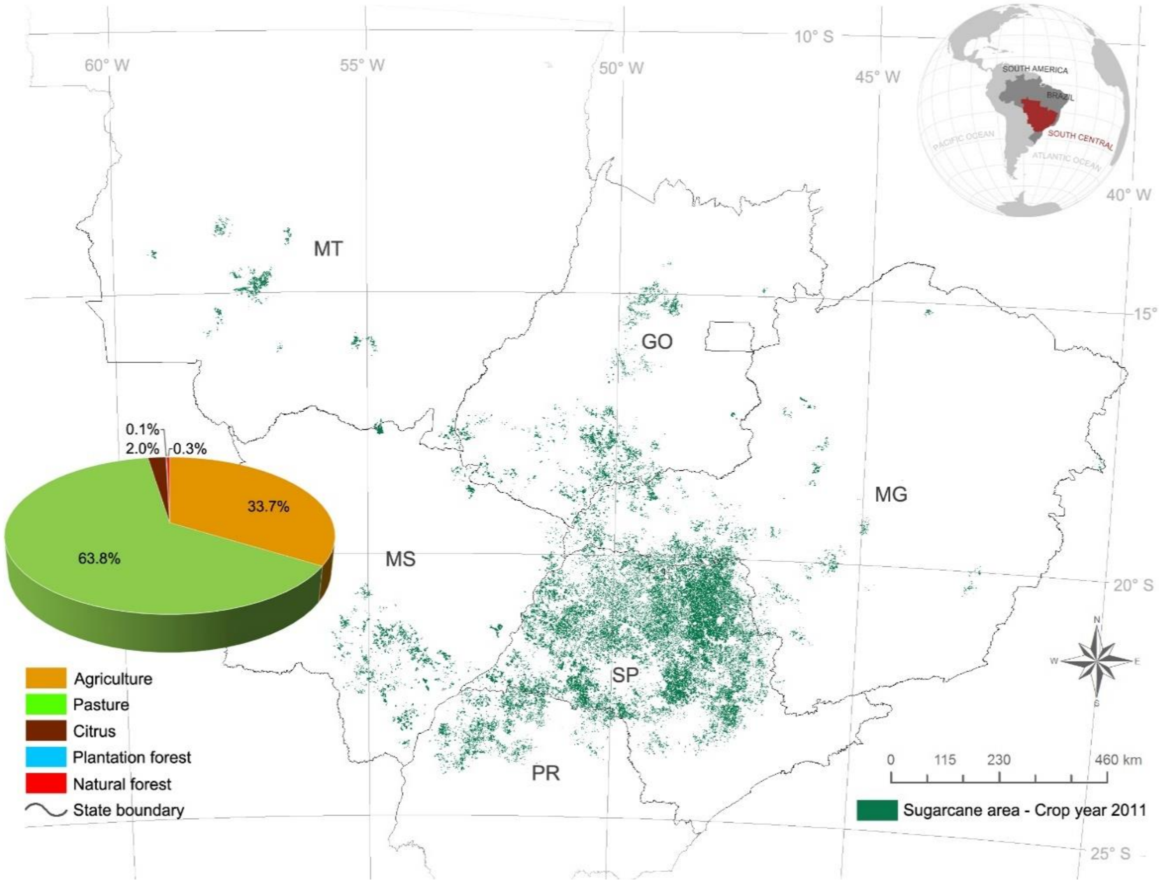

Figure 1. Area of study (crop year 2011) and dLUC of recently established sugarcane plantation (pie chart in percentage) during 2006–2011 in south-central Brazil (Goias–GO; Mato Grosso–MT; Mato Grosso do Sul–MS; Minas Gerais–MG; Parana–PR; and Sao Paulo–SP).

2.2.1 Study boundaries description

Two principal approaches were included: (i) dLUC by expansion of area under sugarcane, and (ii) cultivation of sugarcane from 2006 to 2011 in south-central Brazil. The land use induced by the displacement of previous crop production in other regions was not addressed in this study (i.e., indirect land use change – iLUC). Indirect LUC is a complex process, and its impact is difficult to account for [23]. Remote sensing satellite images were used to monitor the dLUC and to delineate areas under sugarcane cultivated with specific management and harvest practices (e.g., manual harvest with prior burning vs. green mechanized harvest without burning), according to the methodologies proposed by Adami et al. [16], Rudorff et al. [17] and Aguiar et al. [18].

Recently converted areas into sugarcane were grouped into five classes based on the prior land use: a) *Agriculture* – on land under annual crops (i.e., corn and soybean); b) *Pasture* – on grasslands; c) *Citrus* – on plantation including oranges, tangerines and lemon; d) *Plantation forest* – on commercial tree plantations using natural or exotic species like eucalyptus; e) *Natural forest* – on riparian and other forests not associated with plantations.

Regarding specific management and harvest practices of sugarcane, the areas were mapped according to each phase of its agricultural production: a) *Expansion* – the newly planted area to be harvested for the first time; b) *Renovated* – replanted during the current season and to be harvested; c) *Ratoon maintenance* – already harvested more than once, to 5 or 6 harvests prior to renewal; d) *Harvest* – harvested in the current season, either with (BH; burned harvest) or without (GH; green harvest) burning. Details about dLUC and sugarcane cultivation over the 2006–2011 period in south-central Brazil are provided as supplementary material in Appendices A and B, respectively. More information regarding sugarcane crop production can be viewed on CANASAT project website (http://www.dsr.inpe.br/laf/canasat/en).

2.2.2 GHG emissions from sugarcane cultivation

Estimates of GHG emissions from sugarcane cultivation were made in relation to the following practices and inputs: a) direct and indirect N_2O emissions from managed soils: application of synthetic N fertilizer, organic composts (vinasse and filter cake) and mineralization of crop residues left on soil surface after green cane harvest; b) CH_4 and N_2O emissions from pre-harvest burning of residues; c) CO_2 emissions by liming; and d) GHG emissions from diesel consumption by farm operations. Additionally, hidden C costs from the production and transport of synthetic fertilizers (N-P-K), limestone, pesticides (herbicides and insecticides), and diesel were also assessed. The sources of GHG emissions taken into account for each phase of the sugarcane cultivation (*expansion, renovated, ratoon maintenance and harvest*) are shown in Figure 2.

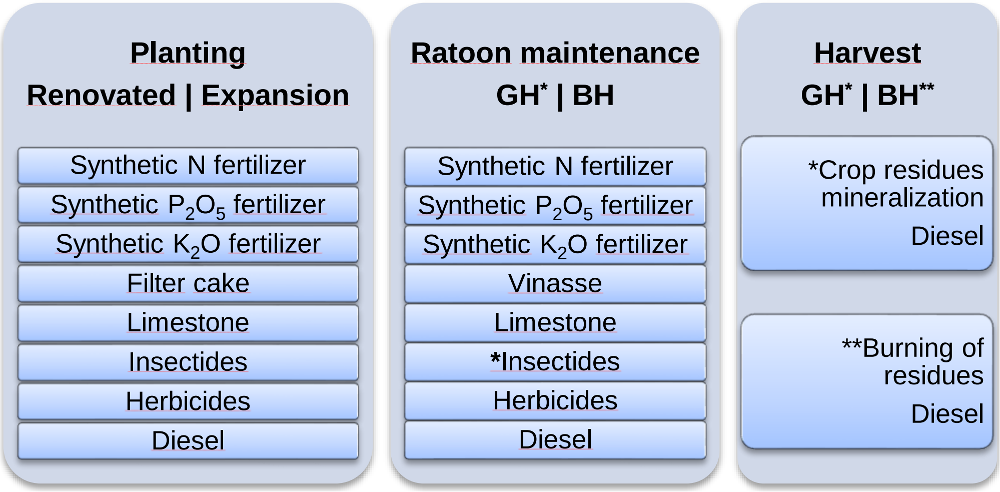

Figure 2. Sources of GHG emissions associated with each phase of the sugarcane cultivation (i.e., planting – expansion and renovated; ratoon maintenance – GH or BH; harvest – GH or BH).

The methodological approach used is similar to that applied by Bordonal et al. [11] to estimate GHG emissions from sugarcane cultivation, which has been distinguished by contrasting the consumption of agricultural inputs according to the specific harvest system (BH or GH). Information regarding the agricultural stage is difficult to measure and gather, and, therefore, presents the highest level of uncertainty due to spatial and temporal variability, and other aspects intrinsic to the agricultural processes. A typical sugarcane production system has been assumed, in which main parameters and amounts of agricultural inputs were based on the agricultural survey data and experts' advice (Table 1), taking into account the differences among phases of sugarcane cultivation (planting, ratoon maintenance and harvesting). Additional information about the magnitude of each agricultural input is given by De Figueiredo and La Scala Jr [9] and Bordonal et al. [11].

Mathematical function by IPCC [21] were used to determine the emission factors (EFs; Table 2), and applied in all cultivated areas (see Appendix B on supplementary material). These equations had to be adapted in some cases because of the country-specific data availability. Results were expressed in teragrams of carbon dioxide equivalent (Tg CO_2eq) for 2006–2011 crop years.

Table 1. Selected parameters per hectare for sugarcane cultivation, according to each phase of its agricultural production (planting, ratoon maintenance and harvest), and the adopted management system (i.e., pre-harvest with burning – BH or mechanized green harvest – GH).

Parameters	Units	Management systems	
		BH	GH
1. Inputs for planting areas			
Fertilizers – with filter cake			
N – 1st applic. [a]	kg	30.0	30.0
P_2O_5 [b]	kg	-	-
K_2O [b]	kg	120.0	120.0
N – 2nd applic. (covering) [a]	kg	30.0	30.0
Filter cake [c]	Mg wb	30.0	30.0
Fertilizers – without filter cake			
N – 1st applic. [a]	kg	30.0	30.0
P_2O_5 [b]	kg	180.0	180.0
K_2O [b]	kg	120.0	120.0
N – 2nd applic. (covering) [a]	kg	30.0	30.0
Others agricultural inputs			
Limestone [a]	Mg	2.0	2.0
Gypsum [b]	Mg	1.0	1.0
Insecticides [d]	kg a.i.	0.16	0.16
Herbicides [d]	kg a.i.	2.2	2.2
Diesel [e]	L	166.7	166.7
2. Inputs for ratoon maintenance			
Fertilizers – with vinasse			
N [a]	kg	100.0	130.0
P_2O_5 [b]	kg	-	-
K_2O [b]	kg	-	-
Vinasse [f]	m^3	140.0	140.0
Fertilizers – without vinasse			
N [a]	kg	100.0	130.0
P_2O_5 [b]	kg	-	-
K_2O [b]	kg	150.0	120.0
Others agricultural inputs			
Limestone [b]	Mg	0.5	0.5
Insecticides [d]	kg a.i.	-	0.16
Herbicides [d]	kg a.i.	2.2	2.2
Diesel [e]	L	16.1	20.4
3. Inputs for harvest			
Diesel [e]	L	94.7	177.2

[a] Values adopted from Bordonal et al. [11];

[b] Amounts were based on a comprehensive survey of average data for sugarcane production systems in the south-central region of Brazil through experts' advice and literature data;

[c] Data taken from De Figueiredo and La Scala Jr [9], who considered a 75% moisture and a filter cake N content of 3.5 kg Mg^{-1} wet basis (wb) or 14 kg Mg^{-1} dry basis (db). The filter cake application for each state of the south-central in Brazil was assumed to be applied in 30% of both expansion and renovation areas;
[d] Values (a.i.: active ingredient) adopted from Macedo et al. [10];
[e] Includes diesel consumption of all operations in each cultivation phase. A detailed description from agricultural operations can be found in Bordonal et al. [11];
[f] Quantities from Macedo et al. [10], who considered a vinasse N content of 0.368 kg m^{-3}. As with filter cake, vinasse was also applied in 30% of both ratoon maintenance areas, either harvested with burning or non-burning practice.

Table 2. Emission factors (in kg CO_2eq per unit) taken into account for each source related to GHG emissions from sugarcane cultivation in south-central Brazil.

Emission sources	**Unit**	**Emission factors (EFs)***		
		Direct emission	**Production**	**Total**
Synthetic N fertilizer [1]	kg	6.20 [a]	4.77 [b]	10.97
Synthetic P_2O_5 fertilizer [2]	kg	-	0.73 [b]	0.73
Synthetic K_2O fertilizer [2]	kg	-	0.55 [b]	0.55
Vinasse [3]	m^3	2.46 [a]	-	2.46
Filter cake [3]	Mg wb	23.36 [a]	-	23.36
Limestone [4]	kg	0.48 [a]	0.01 [c]	0.49
Insecticides [2]	kg a.i.	-	18.70 [b]	18.70
Herbicides [2]	kg a.i.	-	23.10 [b]	23.10
Diesel [5]	L	3.39 [a]	0.58 [c]	3.97
Crop residues mineralization (GH) [6]	Mg $_{SC}$	1.03 [a]	-	1.03
Burning of sugarcane residues (BH) [7]	Mg $_{SC}$	9.90 [a]	-	9.90

* EFs were based on the following references: [a] IPCC [21], [b] Lal [24], and [c] Macedo et al. [10];
[1] It was assumed that 1.325% of the synthetic N fertilizer applied in the sugarcane fields would be emitted into atmosphere as N_2O [21];
[2] These agricultural inputs do not result in direct emissions in sugarcane fields, only those associated with their production and transportation;
[3] For vinasse and filter cake application, 1.425% of the N content is released to the atmosphere as N_2O [21]. A nitrogen content of 0.368 kg m^{-3} of vinasse [10] and 3.5 kg Mg^{-1} wb (wet basis) of filter cake [9] were assumed to calculate the emission factor;
[4] It was considered an emission of 0.13 kg C kg^{-1} of dolomite limestone applied [21];
[5] The following assumptions were considered for diesel combustion: CO_2, CH_4 and N_2O emissions were 74,100 kg CO_2 TJ^{-1}, 4.15 kg CH_4 TJ^{-1} and 28.6 kg N_2O TJ^{-1}, respectively [21];
[6] Total yield of sugarcane (Mg $_{SC}$: megagrams of sugarcane) and straw (db; dry basis) were considered as 82.4 Mg $_{SC}$ ha^{-1} and 140 kg db Mg^{-1}_{SC}, respectively [10,25], with a straw N content of 0.64% [26]. Our assumption is that 20% of N in the dry matter of sugarcane (0.9 kg Mg^{-1}_{SC}) would be mineralized within the period of one year [27,28], corresponding to 0.18 kg N Mg^{-1}_{SC} in green harvested areas. An amount of 1.225% from that N was considered to be emitted as N_2O [21];
[7] EF for residues burning was based on the CH_4 and N_2O emissions of 2.7 and 0.07 (all values in g kg^{-1} of dry matter burned), respectively [29]. A combustion factor of 0.80 has been applied

[21], and a sugarcane and straw yield of 82.4 Mg_{SC} ha^{-1} and 140 kg db Mg^{-1}_{SC} were assumed, respectively [10,25].

2.2.3 Direct land use change from sugarcane expansion

For a comprehensive evaluation of the C emitted or trapped through dLUC, two branches of the ecosystem C reservoirs were taken into account: changes in biomass C pools (above- and below-ground) and in soil C stocks, including N_2O emissions from mineralization of soil organic matter (SOM).

The assessment of dLUC involved data of recently expanded sugarcane upon five prior land uses (details on supplementary material in Appendix A), and the Tier 2 methodology of the IPCC [20] guidelines. Tier 2 involves country-specific emission/removal factors based on the equations used in Tier 1, and relies largely on country-specific estimates of C stocks in initial and final land uses rather than default data [20]. Additional country-specific data were used from the literature rather than the Tier 1 default values. Detailed discussion of Tier 2 method and the country-specific data adopted for estimating changes in biomass and soil C reservoirs are presented in 2.2.3.1 and 2.2.3.2 sections, respectively.

2.2.3.1 Changes in biomass C stocks

Estimates of the above- and below-ground biomass by conversion to sugarcane were based on the assumption that the previous vegetation was completely removed and resulted in near zero amounts of C remaining into biomass. After that, sugarcane is planted soon thereafter increasing the amount of C stored into biomass. The difference between initial and final biomass C pools is used to estimate the changes in biomass C stocks from land use conversion [20]. Tier 2 methods require estimates of the biomass C stocks prior to and following dLUC, based on areas of lands converted in each year of the analyzed period. Reference stocks of the dry matter and the C content regarding each type of land use were based on direct field measurements (Table 3), considering the specific edapho-climatic conditions in Brazil [14,30].

Table 3. Reference stocks of the biomass dry matter (Mg ha^{-1}) and the C content (Mg C ha^{-1}; above- and below-ground) considered for each type of land use: agriculture (annual crops – average for corn and soybean), pasture (genus *Brachiaria* spp.), citrus (average for orchards of 7 and 18 years), plantation forest (*Eucalyptus* spp.), natural forest (Cerrado biome), and sugarcane.

Land use type	Biomass dry matter (Mg ha^{-1})	Carbon content (Mg C ha^{-1})
Agriculture [a]	17.2	8.6
Pasture [a]	10.3	3.4
Citrus [a, b]	53.3	26.6
Plantation forest [a]	75.8	31.4
Natural forest [c]	100.5	50.2
Sugarcane [a, d]	58.4	23.4

[a] Data obtained from Ronquim [14];
[b] Weighted average for 12 orchards of 7 years (25.7 Mg ha^{-1} of dry matter) and 8 orchards of 18 years (94.7 Mg ha^{-1} of dry matter);
[c] There are only few studies focusing on the quantification of biomass in Cerrado biome, especially considering the dry matter in above- and below-ground compartments. Our reference data for above- and below-ground biomass is from Ribeiro et al. [30]. Thus, a default C fraction of 50% has been assumed to convert biomass dry matter to C content [21];
[d] Due to the lack of information about C content (on dry matter) in sugarcane, Ronquim [14] has assumed the IPCC [21] default value of 50%. In our analysis, we considered an average C content of 40% of the dry matter [27,31]. Similar measurements in terms of biomass dry matter in different compartments of sugarcane have also been found by Franco et al. [32].

Equation 1 was applied to estimate the changes in biomass C stocks through dLUC during 2006–2011. All emission or fixation of CO_2 will presumably occur only once following the dLUC, i.e., only in the year of conversion. Results were expressed in Tg CO_2, with a positive value representing a loss of biomass–C, and a negative value indicating C fixation in the biomass.

$$\Delta A_{dLUC\,i} \times (BC_{BEFORE} - BC_{AFTER}) \times 44/12^{*} = \Delta C \text{ biomass} \times 10^{-6}, \quad (1)$$

where, $\Delta A_{dLUC\,i}$ = areas of previous land use (agriculture, pasture, citrus, plantation forest or natural forest) which were converted to sugarcane in a certain year (in ha $year^{-1}$); BC_{BEFORE} = biomass C stock (above- and below-ground) for each land use type prior to conversion (Mg C ha^{-1}); BC_{AFTER} = biomass C stock (above- and below-ground) for sugarcane after conversion (Mg C ha^{-1}); $^{*}44/12$ = conversion factor from C to CO_2; ΔC biomass = gain or loss of biomass C stock (in Tg CO_2) through dLUC over the 2006-2011 period.

2.2.3.2 Changes in soil C stocks

The most dense cultivated sugarcane region in Brazil is located in a moist tropical climate, and in soils classified as low activity clay (LAC), primarily Oxisols and Ultisols [21,33]. Information on changes in soil C stocks due to sugarcane expansion is generally limited, and Mello et al. [13] is one of the few studies which reported the impact of dLUC on soil C dynamics. Based on direct field measurements, Mello et al. [13] estimated specific emission/removal factors by paired comparisons from several sites which were converted from annual crops, pasture and natural forest to sugarcane in south-central Brazil.

IPCC [20] Tier 2 method was applied by incorporating the specific LU emission/removal factors for edapho-climatic conditions in Brazil [13]. Otherwise, the default IPCC impact factor (IF) was assumed when country-specific emission/removal factor was not available (Table 4). To assign the IF from IPCC [21], it was assumed that sugarcane expansion would be occurring under the adoption of full tillage and non-burning practice prior to harvest, since the legal restrictions regarding the pre-harvest burning have been responsible for this trend up to now.

Table 4. Reference soil C stocks (in Mg C ha^{-1}) and impact factors (IFs; dimensionless) for each type of land use (agriculture, pasture, citrus, plantation forest and natural forest) converted to sugarcane in south-central Brazil.

Previous land use type	Climate region	Soil type*	Reference soil C stock (Mg C ha^{-1})**	Impact factor (IF) (20 years)
Agriculture	Tropical moist	Low activity clay soils (Oxisol and Ultisol)	62.0 [a]	1.16 [a]
Pasture			56.6 [a]	0.90 [a]
Citrus			47.0 [b]	0.91 [d]
Plantation forest			45.0 [c]	0.91 [d]
Natural forest			81.0 [a]	0.74 [a]

* Classification of soil type according to IPCC [21] and Manzatto et al. [33];
** Reference C stock at a 0-30 cm depth;
[a] Data taken from Mello et al. [13]. Impact factor can modify the soil C stock up or down, depending on dLUC and the adopted management regime after conversion (soil tillage and C inputs). To predict the IFs from dLUC related to sugarcane, the evaluated sample pairs were derived mostly from sugarcane areas where the practice of burning is adopted prior to harvest [13];
[b] Reference soil C stock from IPCC [21];
[c] Reference soil C stock from Maquere et al. [34];

[d] Each land system use has been classified into the appropriate management. For both replacements, either from citrus or plantation forest, it was deemed that sugarcane plantation would be expanding under adoption of non-burning practice prior to harvest. Based on the IPCC management classification, an IF of 1 should be considered for managed forest (i.e., plantation forest: *Eucalyptus* spp.). A full tillage and medium C inputs ($IF = F_{LU} \times F_{MG} \times F_I = 1 \times 1 \times 1 = 1$) were assigned for citrus, and a full tillage and high C inputs were taken into account for sugarcane ($IF = F_{LU} \times F_{MG} \times F_I = 0.82 \times 1 \times 1.11 = 0.91$).

GHG sources or sinks from changes in soil C stocks through dLUC were estimated using Equation 2, with the positive value representing a C loss and a negative value demonstrating a C sink. Additionally, the changes in soil C stocks following dLUC during 2006–2011 were assumed to stabilize at a new steady state after 20 years [21], with the results being expressed in Tg CO_2eq after 20 years of the last year of dLUC (year 2011).

$$\Delta A_{dLUC\,i} \times [(SC_{Ref}) - (SC_{Ref} \times IF_i)] \times 44/12^{*} = \Delta C\ soil \times 10^{-6}, \qquad (2)$$

where, $\Delta A_{dLUC\,i}$ = areas of previous land use (agriculture, pasture, citrus, plantation forest or natural forest) converted to sugarcane in a certain year (in ha year^{-1}); SC_{Ref} = reference C stock (at 0-30 cm depth) for each land use type before conversion (Mg C ha^{-1}); IF_i = impact factor related to each type of land use change to sugarcane, modifying the C stocks up or down (dimensionless); *44/12 = conversion factor from C to CO_2; ΔC soil = gain or loss of soil C stock expressed in Tg CO_2eq after 20 years (i.e., default timeframe expected to reach equilibrium after land use conversion).

2.2.3.2.1 N_2O emissions from SOM losses

If and when depletion of soil C stock occurs, N_2O emissions from SOM mineralization are also assumed to occur as well [20]. The methodological approach applied by Flynn et al. [35] was used, who reported N_2O emissions only where a soil C depletion has occurred since the soils are not a sink of N_2O. The N released (as N_2O emissions) by net mineralization was calculated using Equation 3, following the calculation of the soil C mineralized over the same time (20 years). N_2O emissions were jointly presented with CO_2 emissions from soil C losses, and the results were also expressed in terms of Tg CO_2eq.

$$\Delta C\ soil \times 1/15^{*} \times 0.01^{**} \times 298^{***} = \Delta_{N\text{-}N2O} \times 10^{-6}, \tag{3}$$

where, ΔC soil = loss of soil C stock per year (in Mg C year^{-1}); *1/15 = the ratio of C to N in SOM is by default 15 [20]; **0.01 = emission factor used for calculating N_2O emissions from N into soils [21]; ***298 = global warming potential applied for converting N_2O emissions in CO_2eq [22]; $\Delta_{N\text{-}N2O}$ = N_2O emissions from annual N released by SOM mineralization, expressed in Tg CO_2eq over a 20-year period.

2.2.4 Accumulated GHG balance by 2030

Assessment of the accumulated GHG balance in south-central Brazil, including all emissions and sinks of C associated to dLUC (biomass and soil C reservoirs, plus N_2O emissions from SOM mineralization) and sugarcane cultivation were summed for each year and allocated over a 20-year period [21]. Changes in biomass C stocks presumably occur once during the year of conversion (see section 2.2.3.1), whereas those in soil C stocks and its N_2O emissions (SOM mineralization) are assumed over a 20-year period (see sections 2.2.3.2 and 2.2.3.2.1). Therefore, the accumulated biomass C stocks over a 20-year period were considered to be constant after the year 2011 (i.e., last year of dLUC). Regarding accumulated GHG emissions from sugarcane cultivation, we took into account the accumulated GHG emission from the 2006–2011 period and summed up to GHG emission of the last year of analysis (2011) until the 20-year period. Results of the accumulated GHG balance by 2030 were expressed in Tg CO_2eq.

2.3 Results and Discussion

Results are discussed in the following sections: sugarcane cultivation (section 2.3.1) and changes on C reservoirs because of dLUC (section 2.3.2), such as biomass C stocks (section 2.3.2.1) and soil C stocks, including its N_2O emissions from SOM mineralization (section 2.3.2.2). An assessment on the accumulated GHG balance up to the year 2030 is provided in section 2.3.3 considering all evaluated criteria. Also, absolute values of GHG emissions and sinks are all detailed on supplementary material in Appendices C, D, E and F.

2.3.1 GHG emissions from sugarcane cultivation

Total GHG emissions (in Tg CO_2eq) are shown in Figure 3, considering all agricultural phases (i.e., renovated; expansion; ratoon maintenance – GH or BH; and harvest – GH or BH) related to sugarcane cultivation during 2006–2011. A total GHG emission of 100.7 Tg CO_2eq was observed for the entire south-central Brazil, with SP accounting for 66.6% (67.0 Tg CO_2eq) of the total emissions, and 33.5% (22.4 Tg CO_2eq) of the emissions in SP resulting from ratoon maintenance under GH system. Emissions from MG and PR were much lower than those of SP, corresponding to an emission of 9.1 and 8.4 Tg CO_2eq over time (i.e., 9% and 8.4% of the total GHG emissions), respectively.

The lowest emissions were observed in GO, MS and MT, with a total amount of 7.3, 5.3 and 3.6 Tg CO_2eq, respectively (Figure 3). In general, the results clearly show that conversion from BH to GH management has increased throughout the 6-year period, since large proportion of gaseous emissions were derived from the ratoon maintenance under GH for all states, except for PR where the pre-harvest burning was the main source of GHG emission.

Considering the annual GHG emission per hectare, a reduction from 2.57 to 2.50 Mg CO_2eq ha^{-1} was noticed in south-central Brazil, which could be explained by the trend observed in the sugarcane sector in adopting the GH instead of BH (details on supplementary material in Appendices B and C). These statistics are higher in comparison with the estimates reported in the literature, because all emission sources (synthetic fertilizers, liming, organic composts, etc.) beyond harvest operations were taken into account herein (see section 2.2.2; Figure 2). Inventorying only GHG emissions from sugarcane harvest operations (i.e., burning of residues and diesel consumption) in the SP state, Capaz et al. [12] reported a reduction from 1.05 to 0.64 Mg CO_2eq ha^{-1} upon conversion from BH to GH for 1990 and 2009, respectively. Few studies on GHG emissions from sugarcane cultivation were conducted in other states of Brazil. Most of them have been focused especially in the SP state, given its overall importance on ethanol production in Brazil [9-12,36,37].

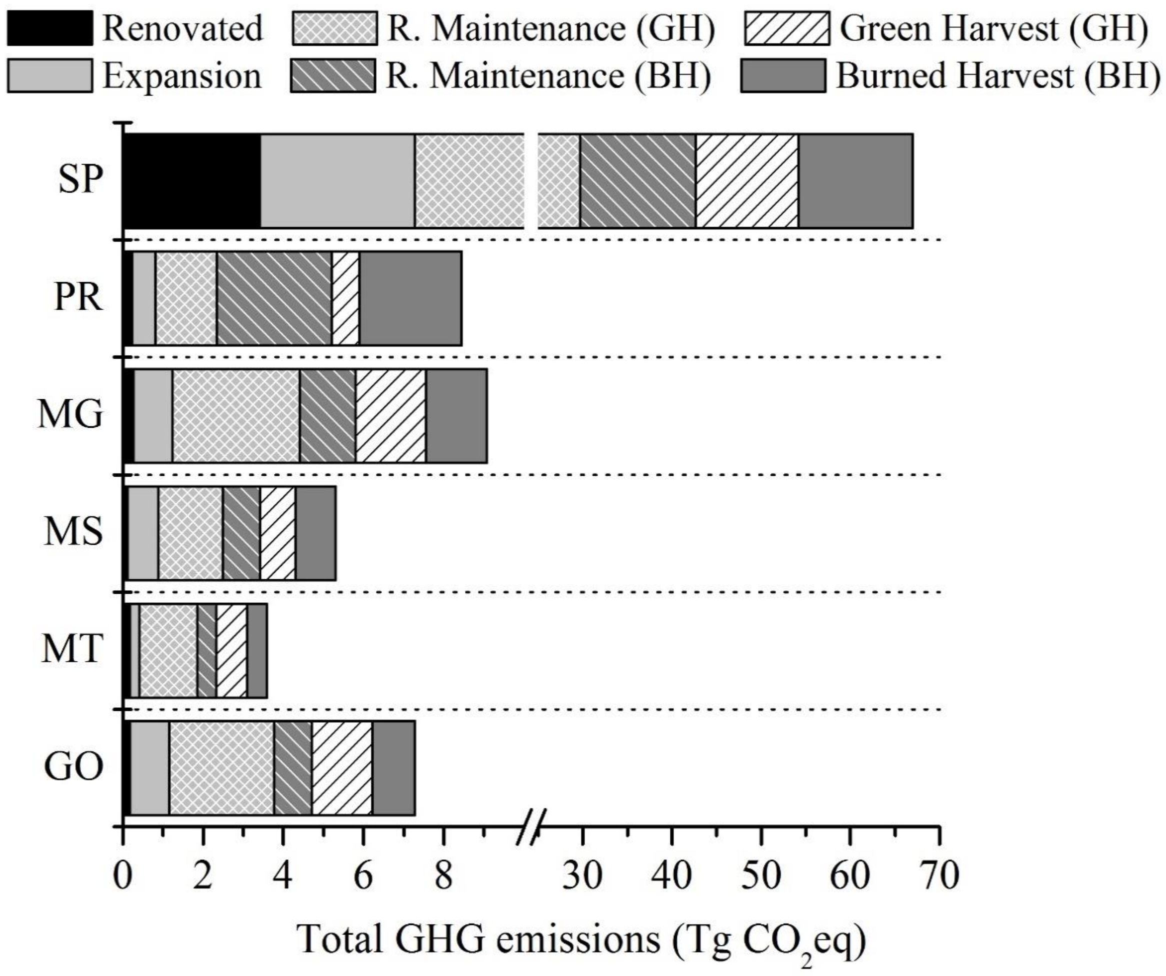

Figure 3. Total GHG emissions (in Tg CO_2eq) over the 2006–2011 period in south-central Brazil (GO, MT, MS, MG, PR and SP), considering all agricultural phases from sugarcane cultivation: renovated, expansion, ratoon maintenance (GH and BH) and harvest (GH and BH).

A detailed discussion regarding each agricultural phase and the contribution of its sources in the GHG emission due to sugarcane cultivation has been presented by Bordonal et al. [37]. Thus, this article presents the absolute values of GHG emission for sugarcane cultivation to advance understanding of the dynamics of GHG balance by 2030 when dLUC is taken into account (details on supplementary material in Appendix C).

2.3.2 Changes on C reservoirs following dLUC

The degree to which recent expansion of sugarcane in the south-central region has contributed to change CO_2 emissions depends largely on the land use type (agriculture, pasture, citrus, plantation forest and natural forest) prior to sugarcane cultivation. When dLUC occurs, soil C stocks could take several years to attain a new equilibrium. Considering a default timeframe of 20 years [21], the overall balance of emissions and sinks (in Mg CO_2eq ha^{-1}) regarding the changes in biomass and soil C pools (including N_2O emissions from SOM mineralization) are shown in Figure 4.

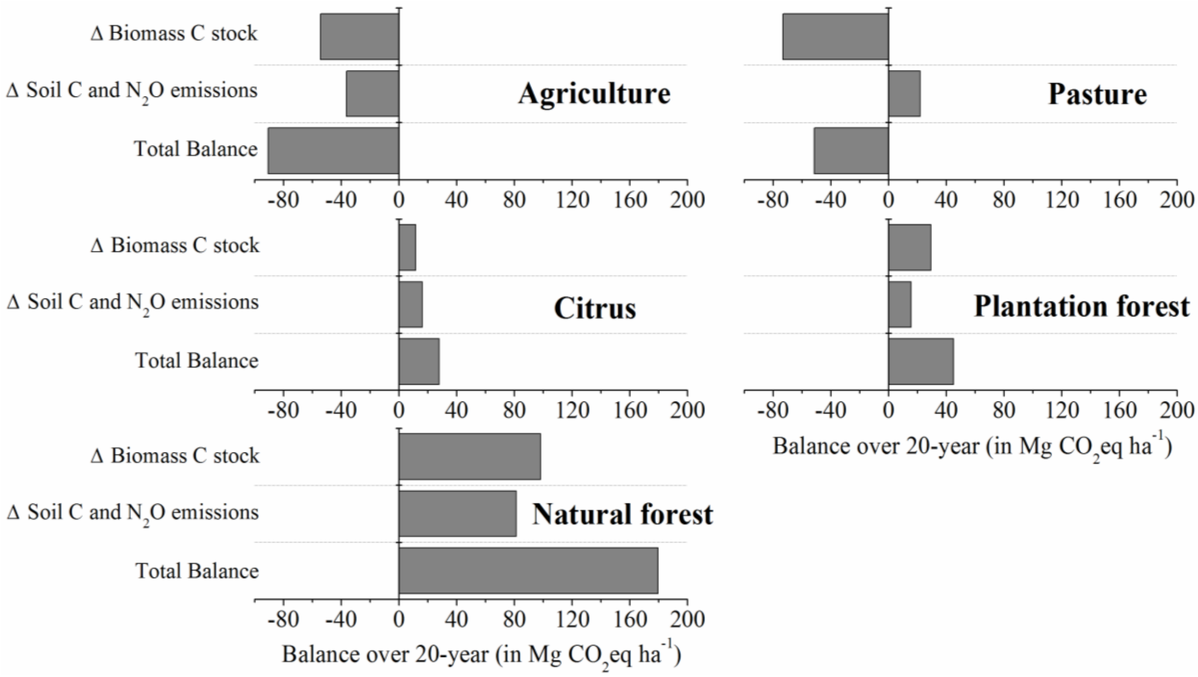

Figure 4. Balance of emissions or sinks (in Mg CO_2eq ha^{-1}) from biomass (CO_2–C) and soil (CO_2–C and N_2O–N) after a 20-year period, due to dLUC from agriculture, pasture, citrus, plantation forest and natural forest to sugarcane during 2006–2011 in south-central Brazil.

Our results show an increase of C reservoirs (biomass and soil) through conversion of arable and pastoral lands into sugarcane, and a decrease of C reservoirs when citrus, plantation forest and natural forest are converted to sugarcane. The highest C sink capacity was observed when dLUC occurred from agriculture (i.e., corn and soybean) to sugarcane, with a balance of -90.6 Mg CO_2eq ha^{-1} by 2030, being -54.3 Mg CO_2eq ha^{-1} fixed into biomass and -36.4 Mg CO_2eq ha^{-1} stored in soils.

On the other hand, the expansion of sugarcane over pastures resulted in emissions of 21.9 Mg CO_2eq ha^{-1} from soils and sinks of -73.3 Mg CO_2eq ha^{-1} into biomass, leading to a balance of -51.5 Mg CO_2eq ha^{-1} up to the year 2030. Unlike the results shown above, the conversion of land use either from citrus or plantation forest to sugarcane indicated a total balance of 28.0 and 45.0 Mg CO_2eq ha^{-1} that would be emitted into the atmosphere, respectively.

The conversion of natural forest to sugarcane would result in a deficit of 179.7 Mg CO_2eq ha^{-1}, being 98.3 Mg CO_2eq ha^{-1} emitted from biomass C loss and 81.4 Mg CO_2eq ha^{-1} emitted from soil C depletion (Figure 4). Anderson-Teixeira et al. [38] reported that annual cropland conversion to perennial crops (e.g., sugarcane) will, in most cases, increase SOC stocks, whereas a decrease in SOC stocks would occur upon conversion of forest or grasslands to perennials, which is in accord with the results presented herein.

The expansion of sugarcane during 2006–2011 indicates a promising strategy for GHG mitigation through a large potential as a sink of C into biomass, especially when sugarcane is established on arable and pastoral lands. Considering 1 ha of sugarcane plantation with an average yield of 66 Mg, Beeharry [39] also reported similar C fixation potential, with an estimated amount of 58.2 Mg CO_2 (15.87 Mg of C) that would be absorbed annually by production of sugarcane biomass. Nonetheless, changes in soil C stocks must also be considered to determine whether sugarcane plantations contribute to curb GHG emission through dLUC [40].

2.3.2.1 Biomass C stocks

Changes in biomass C stocks (in Tg CO_2eq) are shown in Figure 5a, considering the total C fixed or emitted by 2030 through dLUC to sugarcane plantation during 2006–2011 in the south-central region. In general, dLUC had a favorable impact on C fixation in biomass for all states, with emphasis on SP where a biomass C sink of -140.7 Tg CO_2eq was observed. The largest amounts of CO_2 absorbed in SP derived from sugarcane expansion over pastoral (-102.7 Tg CO_2eq) and arable (-39.5 Tg CO_2eq) lands. The states of GO and MG were next in sequence because of a lower biomass C fixation compared to that in SP but similar among them, with an amount of -36.5 and -36.1 Tg CO_2eq fixed into biomass, respectively. Following the trend, the MS and PR had a total C fixation of -29.7 and -23.0 Tg CO_2eq, respectively. The least amount of CO_2 fixation occurred in MT, with -8.5 Tg CO_2eq trapped into biomass.

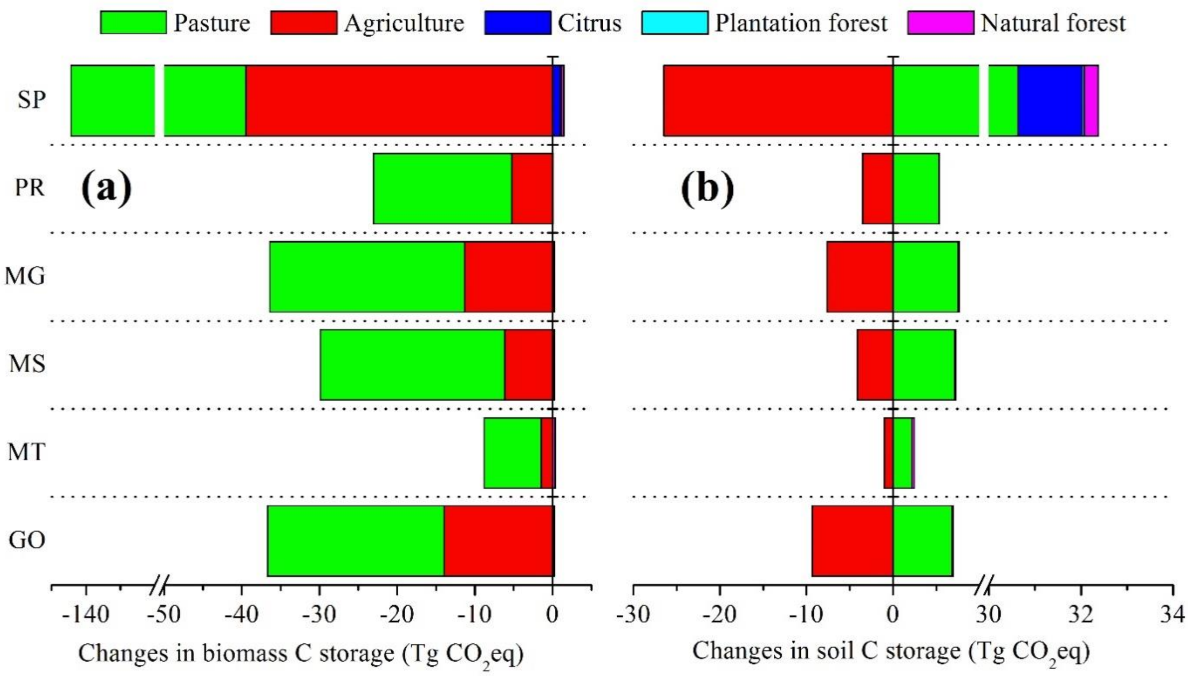

Figure 5. Variations in C storages of biomass (a) and soil (b) after a 20-year period (in Tg CO_2eq) through dLUC from agriculture, pasture, citrus, plantation forest and natural forest to sugarcane during 2006–2011 in south-central Brazil (GO, MT, MS, MG, PR and SP).

With an expanded area of 4.2 Mha during 2006–2011, dLUC to sugarcane plantation might have an even more significant contribution not only to mitigate GHG emissions through C fixation into biomass, but also towards the cooling of local climate [6]. Overall, dLUC has a technical potential of C fixation in biomass of -274.5 Tg CO_2eq by 2030 considering all states in south-central Brazil (Figure 5a). The estimates presented herein indicate an insignificant contribution to CO_2 emissions through dLUC from citrus, plantation forest and natural forest to sugarcane, since total emission of 2.51 Tg CO_2eq associated with these conversions occurred during 2006–2011 (Figure 5a; additional details on supplementary material in Appendix D).

2.3.2.2 Soil C stocks and its N_2O emissions from SOM losses

Total emissions and sinks (Tg CO_2eq) from changes in soil C stocks through dLUC during 2006–2011 was largely driven by sugarcane expansion in pastoral and arable lands in south-central Brazil, showing a soil C depletion of 59.5 Tg CO_2eq and a soil C sink of -52.0 Tg CO_2eq by 2030, respectively (Figure 5b). Regarding land use conversion of arable lands to sugarcane plantation, contributions of SP and GO were estimated at ~51% (-26.5 Tg CO_2eq) and ~18% (-9.3 Tg CO_2eq) of the total C stored in soils, respectively. On the other hand, emissions from SP and MG accounted for about 51.4% (30.6 Tg CO_2eq) and 12.6% (7.5 Tg CO_2eq) of the total C emitted from soils upon conversion of pasture to sugarcane, respectively. The results support the conclusion that the conversion of citrus or forests to sugarcane had a little impact on soil C budget, especially because of low rate of sugarcane expansion into these land use types. For instance, an emission of 1.4 and 1.1 Tg CO_2eq was observed by 2030 upon conversion of citrus and natural forest to sugarcane in the south-central region, respectively (Figure 5b).

Since the expansion of existing sugarcane in south-central Brazil has occurred mainly on pastoral and agricultural lands (details on supplementary material in Appendix A) [16], any increase in soil C stock resulting from conversion of agricultural land into sugarcane is offset by the depletion of soil C stock from conversion of pasture, leading to almost neutral soil C budgets for all states by 2030 (Figure 5b). With exception of the negative C budget of -2.4 Tg CO_2eq for GO, positive C budgets were observed for SP, MS, PR, MT and MG by the year 2030 (Figure 5b; absolutes values are detailed in Appendix E on supplementary material).

Although land use change of pasture to sugarcane leads to a loss of SOC stock after conversion [13,38], SOC accretion may occur in the top 30 cm following the initial loss so that the C debt may be repaid within a century [41]. In this study, potential for soil C accretion upon adoption of recommended management practices during sugarcane cultivation has not been considered. In other words, a conversion from BH to GH system, including the adoption of conservationist management practices (i.e., reduced soil tillage and crop rotation) may accentuate soil C accretion in the most intensively cultivated sugarcane region in Brazil; a potential GHG mitigation of up to 70.9 Tg CO_2eq was reported for the SP state [11].

2.3.3 Accumulated GHG balance from dLUC and sugarcane cultivation

The overall accumulated GHG balance (Tg CO_2eq) for the sugarcane agrosystem was estimated over a 20-year period (Figure 6), taking into account all evaluated criteria (i.e., sugarcane cultivation and the changes in biomass and soil C reservoirs through dLUC during 2006–2011 in south-central Brazil). Accounting for approximately 87.6% of the cumulative GHG balance (217.1 Tg CO_2eq), the highest GHG balance was estimated for the states of SP and PR with an emission of 172.3 and 17.9 Tg CO_2eq by the year 2030, respectively. In comparison, low GHG emission was observed in MG and MT with a small balance of 10.6 and 9.0 Tg CO_2eq, respectively, followed by that in MS and GO with a cumulative GHG balance being almost neutral by 2030.

Considering all states in the south-central region, an accumulated GHG emission of 481.6 Tg CO_2eq resulting from sugarcane cultivation and a biomass C sink of -274.5 Tg CO_2eq were observed by 2030. Further, changes in soil C and related N_2O emissions led to almost neutral C budget, with a slight soil C emission of 10.0 Tg CO_2eq (Figure 6). Including only CO_2 emissions from soils and aboveground and belowground biomass resulting from conversion of native ecosystem (Cerrado wooded) to sugarcane in Brazil, Fargione et al. [8] reported a C debt of 165 Mg CO_2 ha^{-1}. As most of the sugarcane expansion has occurred primarily on pastoral and arable lands, the soil C budget presented in this study would be lower than that reported by Fargione et al. [8]. Almost neutral or even positive C budget reported herein may be explained by a low expansion of sugarcane over native forest (details on supplementary material in Appendix A).

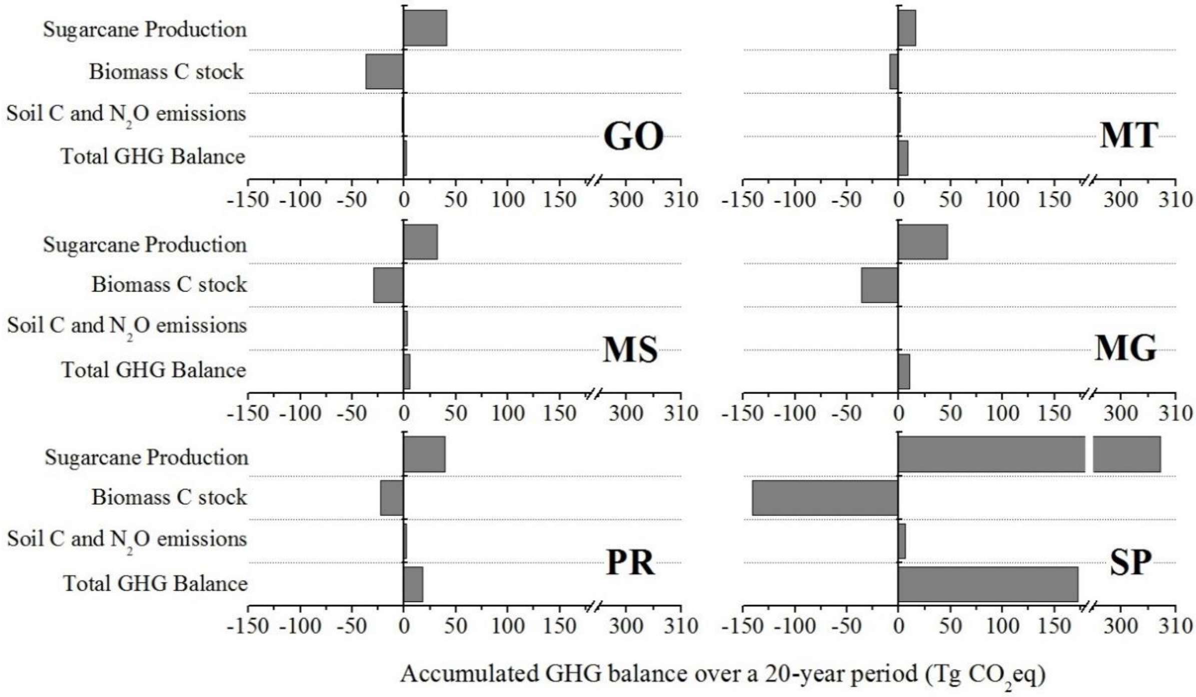

Figure 6. Accumulated GHG balance (in Tg CO_2eq) by the year 2030 associated to dLUC (changes in biomass and soil C stocks, including N_2O emissions) and sugarcane cultivation over the 2006–2011 period in south-central Brazil (GO, MT, MS, MG, PR and SP).

The dynamic of accumulated GHG balance related to dLUC and sugarcane cultivation shown in Figure 7 highlights the specific year (inflection point) in which the GHG balance switched from negative (sinks) to positive (emissions) over the 2006–2030 period. The states of SP, MT and PR became a GHG emitter from the years 2017, 2018 and 2020, respectively. In contrast, states of MG, MS and GO became GHG emitters during the years 2025, 2027 and 2029, respectively. The overall GHG balance was not neutral by 2030, because all C fixed in biomass was offset by GHG emissions from sugarcane cultivation, resulting in a cumulative GHG balance of 217.1 Tg CO_2eq in south-central Brazil (Figure 7; see details in Appendix F on supplementary material).

Although C fixed in biomass has been counterbalanced by that emitted during sugarcane cultivation, the analysis presented did not take into account the CO_2 savings by substitution of fossil fuels. Martinelli et al. [42] reported an avoided CO_2 emission of up 44 Tg CO_2 yr^{-1} due to use of ethanol in Brazil. This figure is more than an order of magnitude higher than the potential GHG mitigation of 1.9 Tg CO_2eq yr^{-1}

(or 70.9 Tg CO_2eq over a 38-year period) due to the adoption of best management practices for sugarcane cultivation in the SP state [11].

With C offset of 9.8 Mg CO_2eq ha^{-1} yr^{-1} through substitution of fossil fuels [8] and taking into account the cumulative GHG balance of 217.1 Tg CO_2eq for a total cultivated area of 192.4 Mha during the 2006–2030 period, an emission avoidance of 1,885 Tg CO_2eq would occur by substituting fossil fuels, which is approximately 8.7 times the GHG balance reported herein. Therefore, a cumulative GHG balance of 217.1 Tg CO_2eq regarding dLUC and sugarcane cultivation could be completely offset by the C savings from sugarcane-based ethanol use in substitution of fossil fuels in Brazil.

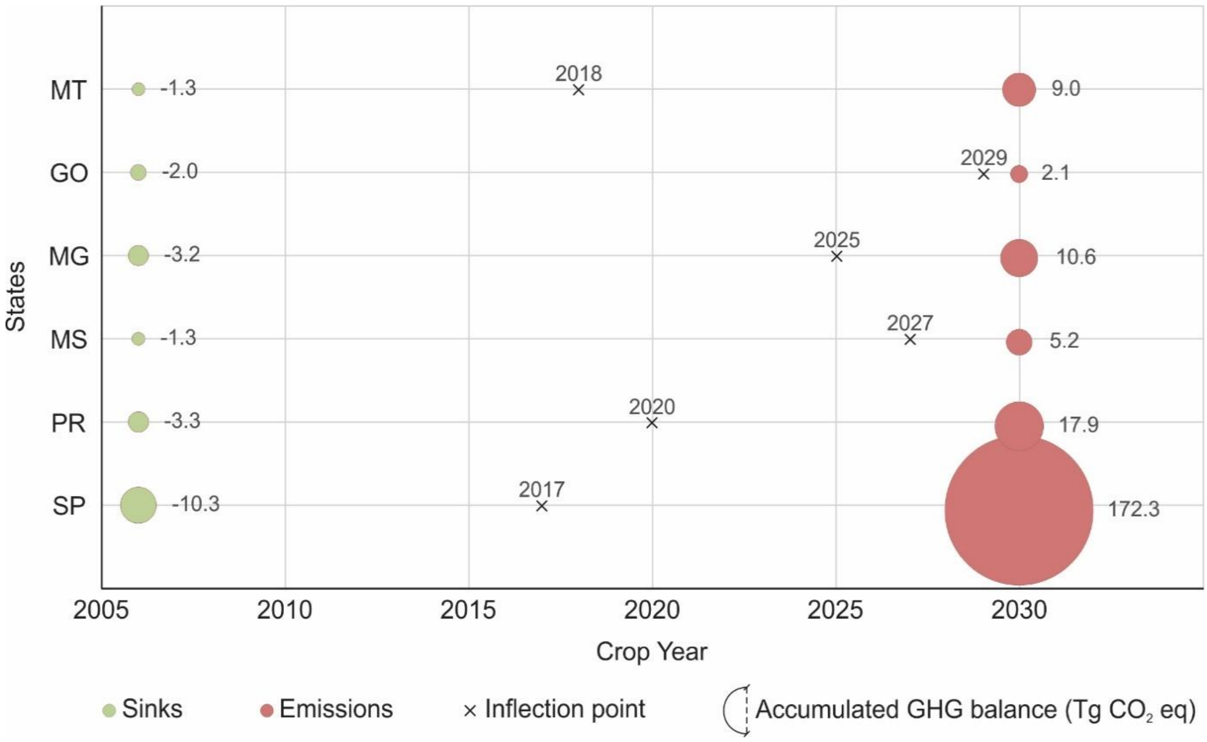

Figure 7. Dynamic of accumulated GHG balance over the 2006–2030 period, related to dLUC of recently established sugarcane plantation and its cultivation during 2006–2011 in south-central Brazil (GO, MT, MS, MG, PR and SP). The negative GHG balance (sinks) is represented by the green spots, whereas the positive GHG balance (emissions) is represented by the red spots, being the inflection point represented by cross (×), which is the specific year of conversion from sinks to emissions.

2.4 Conclusion

Most of the life cycle studies include just the assessment of GHG emissions associated with agricultural production, and dLUC of recently established sugarcane plantation is still negligible. Sugarcane cultivation and its expansion during 2006–2011 in south-central Brazil presented an overall accumulated GHG balance of 217.1 Tg CO_2eq by 2030, including emissions from cultivation activities and emissions/removals due to dLUC. Expansion of sugarcane plantation contributed to attenuate GHG emissions from agricultural production phase, of which 57% were offset by the C storage into biomass through dLUC. Soils had almost neutral effect on C budget by the year 2030, since the increases in soil C stocks through conversion of arable lands into sugarcane were offset by the depletion of soil C stocks from pastoral conversion. Furthermore, such GHG abatement tends to increase for the next years as the non-burning harvest is expected to be phased out in the most dense cultivated sugarcane region in Brazil.

Incentives in public policies are needed to drive the sugarcane expansion towards a sustainable path. As it has been done for sugarcane expansion during 2006–2011, it is imperative to avoid converting citrus, plantation forests and natural forests into sugarcane, while it is desirable to have those expansions on pastures as a key strategy to ensure the environmental benefits of sugarcane ethanol in Brazil.

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CHAPTER 3 – CHANGES IN QUANTITY AND QUALITY OF SOIL CARBON DUE TO THE LAND-USE CONVERSION TO SUGARCANE (*Saccharum officinarum*) PLANTATION IN SOUTHERN BRAZIL

Abstract – The land-use change (LUC) related to sugarcane (*Saccharum officinarum*) expansion could imply significant variations in biogeochemical cycles, including soil carbon (C) stocks beyond the emissions of greenhouse gases (GHG). Thus, the aim of this study was to assess the changes in soil C stocks and in the humification of soil organic matter (SOM) upon conversion of different land uses (coffee, citrus, annual crop and pasture) into sugarcane plantation in southern Brazil. The LUC from coffee to sugarcane depleted soil C stock (0-100 cm) from 124.5 to 97.7 Mg C ha^{-1} (21.5%) after a 3-year period. Similarly, the LUC from citrus to sugarcane depleted the soil C stock (0-100 cm) from 147.7 to 112.8 Mg C ha^{-1} (23.6%) in 4 years. There was no difference in soil C stocks in the 0-100 cm layer upon conversion of annual crop and pasture to sugarcane. On the other hand, a significant difference in soil C stock in the 0-20 cm layer was observed upon conversion of pasture to sugarcane, with depletion from 30.3 to 17.0 Mg C ha^{-1} (43.9%) in 8 years. Laser-Induced Fluorescence Spectroscopy (LIFS) was used to assess the humification of SOM, showing a high degree of humification as greater was the depletion of soil C stock. Further, sugarcane plantation increased the humification in sub-soil as compared with other agricultural land uses, except in pasture. The latter had lower humification of SOM in the surface layers of soil compared to that under sugarcane established on pasture. Increase in humification with increase in soil depth was observed for pasture and all areas under sugarcane plantation, indicating a possible accumulation of more recalcitrant C in sub-soil. These results indicate that expansion of sugarcane over agroecosystems may impact the sustainability of ethanol production because of LUC-induced depletion of soil C stock and degradation of soil quality.

Keywords: sugarcane expansion; ethanol production; greenhouse gas; soil organic matter; Laser-Induced Fluorescence Spectroscopy; sustainability.

3.1 Introduction

A substantial increase in the atmospheric concentration of carbon dioxide (CO_2) and other greenhouse gases (GHGs) has occurred since the industrial revolution, triggered especially by burning fossil fuels and the land-use change due to the expansion of agricultural lands. Soil carbon (C) is a large component of the global C cycle and its management affects the atmospheric CO_2 levels (Lal, 2004). A long-term solution in developing alternatives to fossil fuel has been the renewable energy sources, such as Brazilian sugarcane ethanol (Goldemberg, 2007), which also accelerates the expansion of new agricultural lands.

Brazil is a leading producer of sugarcane ethanol, with a total cultivated area of around 9.1 million hectare (Mha) in the 2015/2016 season, and São Paulo State accounts for over 52% of the total area (CONAB, 2015). The sugarcane ethanol production is projected to increase from the current 21 to 61.6 billion liters by 2021 (Goldemberg et al., 2014). Despite numerous strategic advantages of sugarcane ethanol through replacement of fossil fuels (Börjesson, 2009; Seabra et al., 2011), the rapid expansion of sugarcane plantation has raised questions regarding its sustainability (Lapola et al., 2010).

Both land-use change (LUC) and agricultural sector have been the major source of GHG emissions in Brazil, being responsible for ~80% of total emissions in 2005 (MCT, 2010). Assessing the impact of LUC of about 4 Mha during 2005-2010 in south-central Brazil, Adami et al. (2012) observed that ~95% of sugarcane expansion has occurred on pastures (69.7%), annual crops (25%) and citrus (1.3%). The potential benefits of biofuels to offset C emissions are highly reliant on the LUC triggered by the expansion of bioenergy crops (Lapola et al., 2010). Soils can be a sink or source of C depending on the LUC and management practices (Batlle-Bayer et al., 2010).

An important management issue is the extent of soil C dynamics when diverse agricultural systems are converted into sugarcane plantation. Regional changes on coverage and land-use driven by sugarcane expansion may affect the biogeochemical cycles, including soil C stocks and GHG emissions (Don et al., 2012; Mello et al., 2014). The effects of LUC and management practices in agricultural systems can also affect the quality of soil organic matter (SOM) (Dieckow et al., 2009; Panosso et al., 2011, Segnini et al., 2013).

Changes in soil C stocks are not usually accounted in any life cycle analysis (LCA) of sugarcane plantation, but have a large impact on the results (Anderson-Teixeira et al., 2009). Thus, inclusion of the LUC-induced emissions into GHG balance of sugarcane cultivation should be a key priority in the ethanol production chain (Bordonal et al., 2015). Biofuels can create a “carbon debt” and reduce the C savings achieved by replacing fossil fuels, depending on how they are produced (Fargione et al., 2008; Searchinger et al., 2008; Mello et al., 2014).

Therefore, field experiments are needed to scale the agrosystems responses to better understand the impact of LUC on C cycle in regional and national scales. The data of these experiments are critical for supporting public policies and decision making related to the land-use and management. Thus, the objective of this study was to assess the changes in soil C stocks and in the humification index of SOM upon conversion of diverse land uses (coffee, citrus, annual crop and pasture) into sugarcane plantation in southern Brazil.

3.2 Material and Methods

3.2.1 Description of the study areas

The field experiment was conducted on a Typic Haplustult (USDA, Soil Taxonomy) located in the Mococa region, São Paulo (SP) State, Brazil. The climatic classification of the region is B_1rB_4a (Thornthwaite, 1948), which is tropical moist with an average annual temperature of 21°C. The mean annual precipitation is approximately 1500 mm and most rainfall is received between October and March with a relatively dry period between April and September. The dynamic of the land-use occupation displayed in Figure 1 represents the evolution of the main agrosystems (coffee, citrus, annual crop and pasture) converted into sugarcane plantation in the Mococa region for years 1988 and 2014.

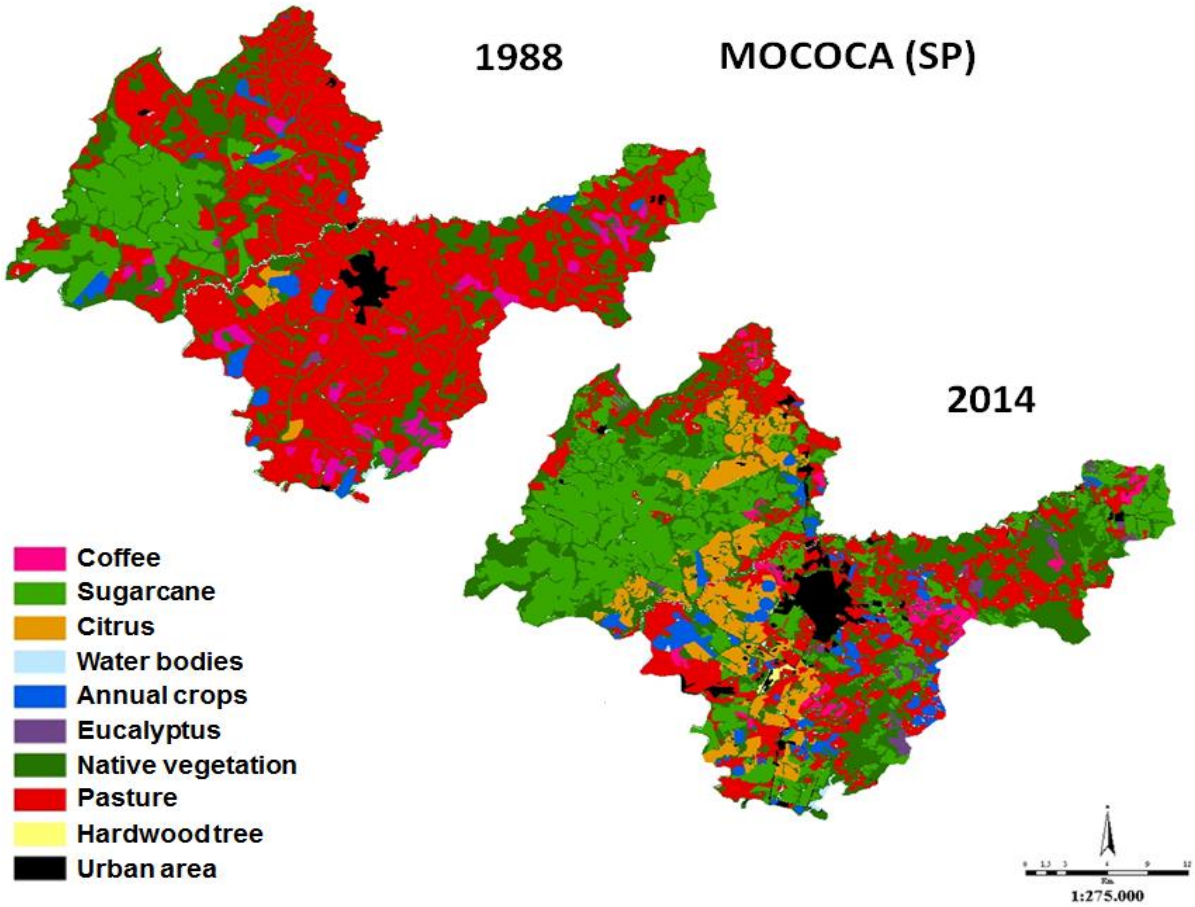

Figure 1. Changes in the land-use occupation for years 1988 and 2014, associated with the main agrosystems converted into sugarcane plantation in the Mococa region (SP) of southern Brazil (Source: Carbcana Project; http://www.cnpm.embrapa.br/projetos/carbcana).

The soil physical characterization for each paired plot is presented in Table 1. With focus on the process of LUC (i.e., coffee, citrus, annual crop and pasture) to sugarcane plantation, the selection criteria were based on the availability of: information on historic land-use, reference or baseline areas with similar edaphoclimatic conditions, i.e., topography, weather and soil type (in particular soil texture, see Table 1) and, of sugarcane plantation in close proximity. Four paired plots were selected under diverse agricultural systems, so that soil samples were obtained in the same location at different times for each pair. In addition, the types of land-use conversion into sugarcane (e.g., comparison pairs) were chosen as independent and are not comparable among themselves.

Table 1. Soil physical characterization for 0-20 and 0-100 cm depths associated with conversion of diverse agrosystems to sugarcane plantation in southern Brazil. Values represent the mean values of five replicates ± standard deviation.

Paired plots		Physical attributes							
		Soil bulk density (ρb) (Mg m^{-3})		Soil texture					
				Clay (g kg^{-1})		Silt (g kg^{-1})		Sand (g kg^{-1})	
		0-20	0-100	0-20	0-100	0-20	0-100	0-20	0-100
1	Coffee	1.42±0.17	1.37±0.05	205±3	240±2	97±2	91±1	699±3	670±2
	Sugarcane	1.29±0.09	1.46±0.09	142±2	175±1	31±2	28±1	827±3	796±1
2	Citrus	1.31±0.09	1.25±0.08	455±3	498±2	109±2	108±2	436±2	394±1
	Sugarcane	1.26±0.07	1.18±0.13	416±1	436±1	105±2	110±2	479±2	455±3
3	Annual crop	1.41±0.12	1.44±0.10	295±6	400±5	71±1	64±1	634±6	537±4
	Sugarcane	1.28±0.08	1.36±0.02	326±12	375±11	51±1	53±1	623±12	573±10
4	Pasture	1.37±0.06	1.39±0.01	107±1	139±1	70±1	74±2	823±2	787±2
	Sugarcane	1.39±0.10	1.41±0.08	84±3	139±3	89±1	88±2	828±4	772±4

Table 2 summarizes major characteristics of paired comparison over time since the initial LUC and the historic land-use and management for each agricultural system. The historic land-use and management for the agricultural systems prior to conversion into sugarcane is described as follows:

1) Coffee – it was established with *Coffea arabica* L. cv. Catuaí in 2002 after intensive soil tillage, at 3.5×1 m spacing. Weed control in the inter-row zone achieved by using glyphosate herbicide without soil disturbance for 8 years. In 2010, part of the area was converted into sugarcane;

2) Citrus – it was established with *Citrus sinensis* L. Osbeck in 1994 after intensive soil tillage, at 6×4 m spacing. Soil in the inter-row was covered with grass vegetation (*Brachiaria* spp.), which was mowed annually for 15 years without any soil disturbance. In 2009, part of this area was converted into sugarcane;

3) Annual crops – it involved cultivation of maize (*Zea mays* L.) during the summer seasons and in rotation with vegetables such as onion (*Allium cepa* L.), sugar beet (*Beta vulgaris*) and carrot (*Daucus carota*). This area was under crop cultivation with intensive soil tillage (e.g., 2-3 times per year) for several years. In 2006, an adjacent area under the same land-use and management was converted into sugarcane;

4) Pasture – it was under *Brachiaria decumbens* (*Brachiaria decumbens stapf*) for more than 10 years. It was a degraded pasture without management (e.g., fertilizers application) or any soil disturbance in the last 10 years. In 2005, part of the area was converted into sugarcane.

Table 2. Description of the agricultural management for paired plots associated with each land-use change (LUC) to sugarcane plantation in southern Brazil.

Comparison Pairs[a]	Previous land-use	Management Description	Time since initial LUC (years)	Current land-use	Management Description
1	Coffee	Perennial tree crop without soil disturbance in the last 8 years.	3	Sugarcane	Green mechanized harvest (non-burning) implemented after intensive soil tillage.
2	Citrus	Perennial tree crop without soil disturbance in the last 15 years.	4	Sugarcane	Green mechanized harvest (non-burning) implemented after intensive soil tillage.
3	Annual crops	Intensive soil tillage (2-3 times per year) and, crop rotation between maize and horticultural crops.	7	Sugarcane	3 years under green mechanized harvest (non-burning) and adoption of manual harvest with burning in the last 4 years, with the conventional soil tillage every 5 years.
4	Pasture	Degraded and without soil disturbance in the last 10 years.	8	Sugarcane	6 years under manual harvest with burning and adoption of green mechanized harvest (non-burning) in the last 2 years, with the conventional soil tillage every 5 years.

[a] Sampling performed on April 22nd, 2013.

3.2.2 Soil sampling and analysis

Soil samples were collected in April 2013 for four paired plots, representing land-use conversion of: (1) coffee, (2) citrus, (3) annual crops and (4) pasture into sugarcane plantation (Table 2). Soil samples were obtained from between the crop rows at five spatial replicates per area and at four soil depths (0-10, 10-20, 20-60 and 60-100 cm), with a total of 40 samples for each paired plot. Figure 2 denotes the procedures of soil sampling conducted for paired plots under coffee and sugarcane established after coffee, considering a soil depth of up to 100 cm (0-10, 10-20, 20-60 and 60-100 cm layers).

Figure 2. Procedures of soil sampling conducted for analyses of total C content, soil bulk density and humification index of SOM in a soil depth of up to 100 cm, considering the paired plots under coffee and sugarcane established after coffee in southern Brazil.

Soil samples were analyzed for total C content, soil bulk density (ρ_b) and humification index (H_{LIFS}) of SOM. Soil sampling, sample preparation, and storage pending analyses followed the protocol established by EMBRAPA (1997). Soil ρ_b was determined on undisturbed samples collected by a core sampler with core size of 5.0 cm in internal diameter and 4.0 cm in height (EMBRAPA, 1997). Undisturbed core samples were composited for evaluation of dry soil weight (105 ºC). After air-drying and gentle grinding, soil samples were sieved through a 2-mm sieve. 10 g of each sample was finely ground and sieved through a 0.25-mm sieve for measurements in duplicate. Soil ρ_b was calculated by dividing the dry weight by the core volume (Blake and Hartge, 1986), and the total C content was determined by the dry combustion method using a Carbon Analyzer-LECO model CR 41 (Nelson and Sommers, 1982).

3.2.3 Soil C stock calculation

In addition to the total C content, soil C stocks were also calculated for 0-20 and 0-100 cm soil depths by multiplying the C content by the soil ρ_b and the layer thickness. Soil C stocks were also computed on equal mass basis to account for variations in ρ_b after LUC (Ellert and Bettany, 1995).

3.2.3.1 Annual rates of soil C loss/accumulation

The annual rates of C loss or gains associated with LUC of diverse agricultural systems (e.g., coffee, citrus, annual crop and pasture) into sugarcane plantation were calculated for the 0-20 and 0-100 cm depths by using Equation 1. Positive values indicate a soil C stock accumulation and negative soil C stock depletion:

$$C_{\ loss/accumulation} = \frac{C_{current} - C_{reference}}{T_{LUC}} \tag{1}$$

where, $C_{\ loss/accumulation}$ is the annual rate of soil C loss or accumulation following the LUC (Mg C ha^{-1} year^{-1}), $C_{current}$ is the C stock under sugarcane plantation after

LUC (Mg C ha^{-1}), $C_{reference}$ is the referential C stock before LUC (Mg C ha^{-1}), and T_{LUC} is the time since the initial LUC (years).

3.2.4 Humification index by Laser-Induced Fluorescence Spectroscopy

The humification of SOM was assessed by using the Laser-Induced Fluorescence Spectroscopy (LIFS) technique (Milori et al., 2006; Panosso et al., 2011; Segnini et al., 2013). The portable LIFS system is a lab-made equipment developed by Brazilian Agricultural Research Corporation - Embrapa Instrumentation. It comprises a diode laser (Coherent - CUBE) emitting at 405 nm (50 mW), an optical shutter, a bifurcated optical fiber bundle with seven optical fibers in a stainless steel ferrule: six illumination fibers around one read fiber (Ocean Optics), a high sensitivity mini-spectrometer (USB4000 - Ocean Optics), an adjustable optical filter, and a notebook. The resolution of the system was around 10 nm for all acquisition ranges (475–800 nm). In addition, software was developed to control the laser, the shutter, and spectrometer parameters such as integration time and number of averages for each measurement (Santos at al., 2015).

The measurements were done in triplicate for each soil sample and data was acquired according to the procedures described by Santos at al. (2015). The ratio between the area under fluorescence emission spectrum (range 475 and 800 nm) and C concentration (in g kg^{-1}) for each sample was considered as an indicator of humification of SOM (H_{LIFS}), being expressed in arbitrary units (a.u.).

3.2.5 Statistical analysis

The experiment was conducted according to a split-plot design with five replications using a fully randomized design. Equation 2 gives the linear statistical model used for the split-plot design:

$$Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \gamma_{k(i)} + \varepsilon_{ijk} \quad (2)$$

where, μ is the mean, α_i is the whole-plot treatment effects, β_j is the split-plot treatment effects, $(\alpha\beta)_{ij}$ is the interaction effects, $\gamma_{k(i)}$ is the whole-plot errors, and ε_{ijk} is the split-plot errors.

The main treatments consisted of a pair of crops (paired plots), involving first a long-established crop (reference land-use) and the second a sugarcane plantation established after the LUC. The secondary or sub-plots were the four soil depths (0-10, 10-20, 20-60 and 60-100 cm). The treatments and interactions were analyzed by computing analysis of variance and the means were compared with Tukey's test at the 5% significance level. The data were log-transformed to achieve homoscedasticity and statistical analysis was performed using SAS (SAS version 9, SAS institute, Cary, NC, USA).

3.3 Results and Discussion

3.3.1 Total C content and soil C stocks

The data on total C concentrations (g kg^{-1}) for four soil depths (0-10, 10-20, 20-60 and 60-100 cm) for each paired comparison are shown in Figure 3. The difference in the total C concentration was significant ($p < 0.05$) in the 20-60 cm soil layer upon conversion of coffee into sugarcane. Total C concentration in the soil profile indicated reduction under coffee in the 60-100 cm soil layer and under sugarcane (coffee) in all soil layers below 10 cm depth ($p < 0.05$). Higher total C concentrations in sub-soil layers are expected under coffee agrosystem, because of inter-row weed control with herbicides without any soil disturbance (e.g., 8 years) with high input of biomass-C in the sub-soil through dead roots (Bicalho, 2011). Moreover, inputs of biomass-C in monoculture coffee is primarily through litterfall and exudation of fine roots. Thus, root distribution and activity determine the enrichment of soil C stock (Hergoualc'h et al., 2012). Root distribution in a coffee plantation is relatively homogenous in the top 60 cm of soil (Hergoualc'h et al., 2012), in which are concentrated 75% of the total fine root biomass of the top 100 cm depth (Siles et al., 2010).

The LUC of citrus to sugarcane resulted in a significant change in C concentration in 10-20, 20-60 and 60-100 cm layers ($p < 0.05$). Reduction in C concentration in the soil profile was observed in 60-100 cm depth for citrus and in 20-60 and 60-100 cm layers for sugarcane (citrus). The maintenance of the soil cover with grass (*Brachiaria* spp.) in the inter-rows and without any soil disturbance increased C concentration in the sub-soil under citrus compared with that under sugarcane (citrus). Similarly, greater differences in total C concentration in sub-soil are observed upon conversion of citrus into sugarcane in comparison with those in the transition of coffee into sugarcane (Figure 3), which does not have any soil cover in the inter-row zone (Table 2).

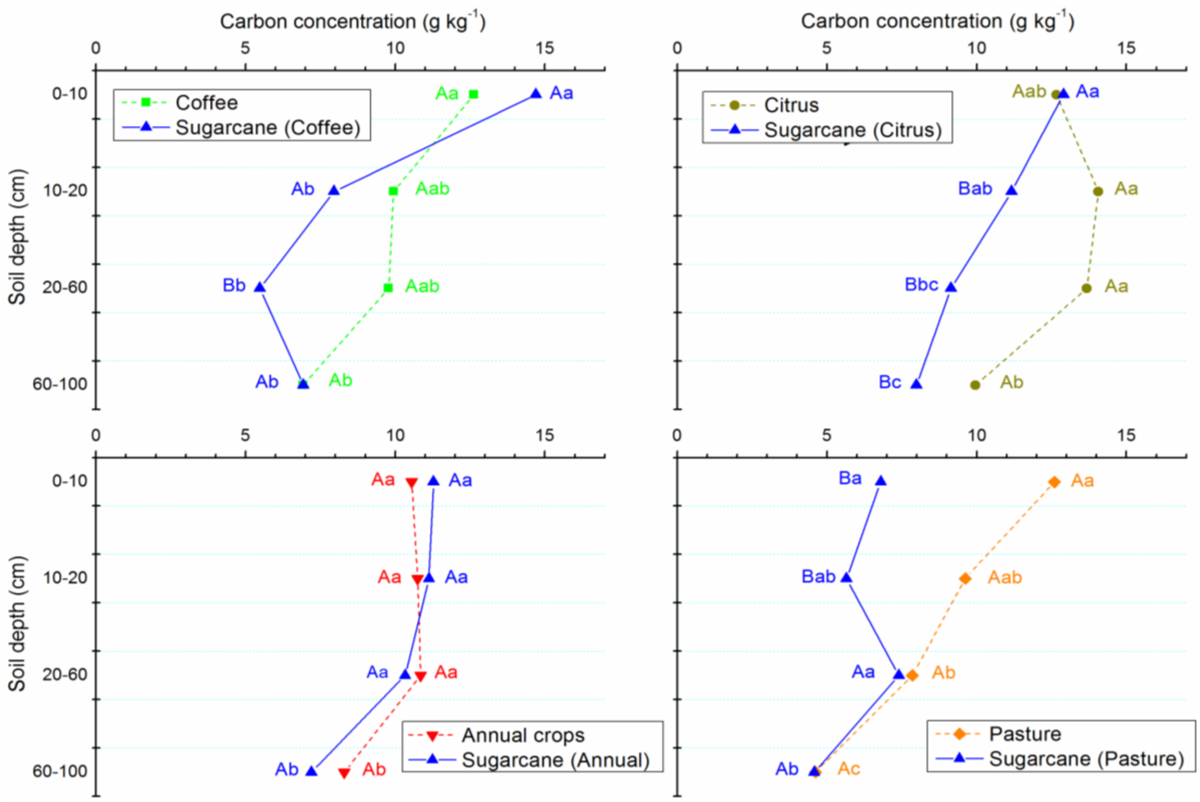

Figure 3. Soil carbon concentrations (g kg^{-1}) for 0-10, 10-20, 20-60 and 60-100 cm layers under land-use change (LUC) of coffee, citrus, annual crop and pasture into sugarcane plantation in southern Brazil. Each data point is the mean values for five replicates. Means followed by different capital letters indicate differences among land-use systems (crops), and means followed by different lower case letters indicate difference among soil layers (Tukey test: $p < 0.05$).

After evaluating the effect of a 6-year period of permanent cover species between the citrus trees, Balota and Auler (2011) reported that strip tillage with *Brachiaria* spp. increased soil organic carbon (SOC) by up to 70 % in the inter-row zone compared to the antecedent value. Reduction in the degree of soil disturbance associated with cover species between the trees in perennial crop systems can change soil aggregation, and residue amounts and rooting depth, thereby affecting soil microbial diversity and C concentration (Dick, 1992; Balota and Auler, 2011). Similarly, the aggregate stability is improved within the rhizosphere, which produces high levels of macroaggregation (Bronick and Lal, 2005). Perennial tree crops (e.g., citrus and coffee) have a deeper root biomass compared to that under sugarcane, which in turn has many effects on soil aggregation and SOC levels. This is a high researchable priority.

SOC concentration was significantly lower in the upper soil horizons (0-10 and 10-20 cm) under sugarcane than that of the adjacent pasture plots ($p < 0.05$) (Figure 3). These results are in agreement with those obtained by Franco et al. (2015), who reported the average SOC losses from 15.5 to 12.7 g kg^{-1} (18%) in the upper 30 cm of soil upon conversion from pasture to sugarcane in a soil of the Brazilian Cerrado region. Considering the C concentration in the soil profile, decline of SOC was observed at 20-60 and 60-100 cm depths under pasture rather than for 60-100 cm depth under sugarcane established on pasture (Figure 3). Decline in SOC concentration in the surface layers under sugarcane (pasture) is attributed to a high rate of decomposition due to soil disturbance during the planting operation (Osher et al., 2003). Conversely, pasture area had no soil tillage over the last 10 years (Table 2). The decomposition of SOM is accentuated by soil disturbance in sugarcane replanting period (La Scala Jr et al., 2006; Silva-Olaya et al., 2013; De Figueiredo et al., 2015), because tillage increases interaction between SOM and oxygen (Silveira et al., 2000; Murty et al., 2002).

There is no difference ($p > 0.05$) in soil C concentration among land uses at any soil depths for conversion from annual crop to sugarcane. On the other hand, decline in soil C concentration was observed in 60-100 cm depth for both land-use systems compared to that in the surface layers (Figure 3). With regards to the depth distribution of soil C in diverse land-use systems, there was a trend of decline in C concentrations at depth. Similar results have been reported for other studies (Boddey et al., 2010; Carvalho et al., 2010; Segnini et al., 2013; Sá et al., 2015).

The overall effects of the LUC (conversions of coffee, citrus, annual crop and pasture into sugarcane) on soil C stocks for 0-20 and 0-100 cm depths are shown in Figure 4. In accord with previous studies (Rossi et al., 2013; Mello et al., 2014; Franco et al., 2015), the conversion of pasture into sugarcane decreased soil C stock from 30.3 to 17.0 Mg C ha^{-1} (43.9%) in the 0-20 cm layer ($p < 0.05$), with a mean rate of a soil C loss at 1.66 Mg C ha^{-1} year^{-1} (Table 3). Assessing the effects of sugarcane expansion into pastures on soil C stocks in Brazilian Cerrado, Franco et al. (2015) also observed a loss in soil C stock of 29.1 Mg C ha $^{-1}$ (40%) in the 0-30 cm layer over 20 years. This period included more than 10 years under burned harvest management, which severely depletes soil C stocks (Robertson and Thorburn, 2007; Galdos et al., 2009).

Table 3. Rate of accumulation or loss of soil C stocks (Mg C ha^{-1} year^{-1}) for different scenarios of land-use transition. Positive values indicate accretion and negative depletion of soil C stocks.

Rate for different land-use transitions (Mg C ha^{-1} year^{-1})	Soil depth (cm)	
	0-20	0-100
Coffee → Sugarcane	-0.28	-8.95
Citrus → Sugarcane	-0.85	-8.74
Annual crops → Sugarcane	0.23	-1.23
Pasture → Sugarcane	-1.66	-2.07

Among several factors influencing soil C stock with LUC, Murty et al. (2002) reported the effects of management practices (e.g., crop residue management and tillage operations) among principal causes of change in soil C stocks at several sites. In accord with data presented herein for land uses under pasture and sugarcane (pasture), the lack of soil disturbance in pasture over the last 10 years and the adoption of burned harvest system during 6 years in sugarcane established on pasture may explain higher C stocks under pasture than that under adjacent sugarcane area (Table 2; Figure 4).

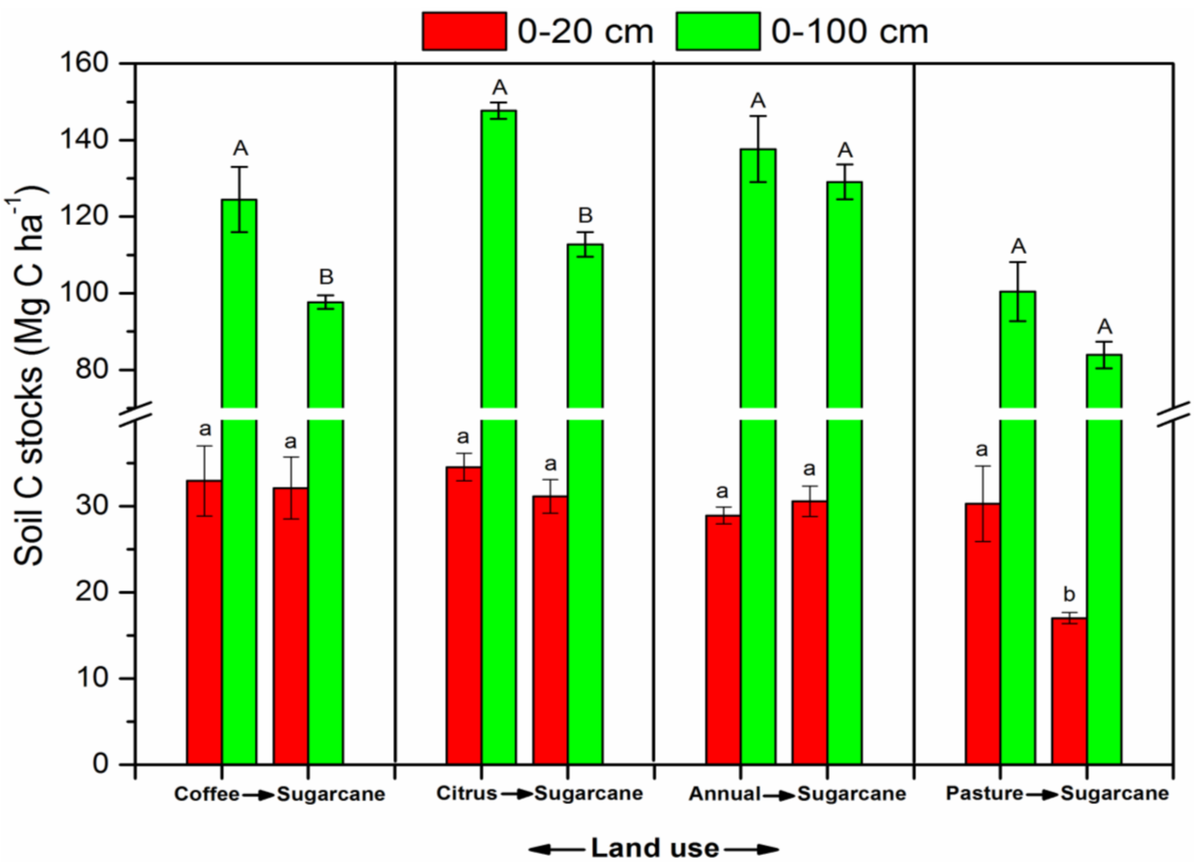

Figure 4. Soil carbon stocks (Mg C ha^{-1}) for 0-20 and 0-100 cm depths, following the land-use change (LUC) of coffee, citrus, annual crop and pasture into sugarcane plantation in southern Brazil. Mean values are averages of five replicates. Means followed by different capital letters indicate differences among each comparison pair for the 0-100 cm and those followed by different lower case letters indicate difference among each comparison pair for the 0-20 cm soil depth (Tukey test: $p < 0.05$).

In some cases, soils under sugarcane could have similar or larger C stocks than those under pasture, depending on the status of pasture degradation, the time since land-use transition and the adoption of best management practices in sugarcane fields (e.g., green cane management and no-tillage). While inappropriate management practices my deplete soil C stocks, adoption of best management practices can reduce soil C losses upon conversion of pasture into sugarcane (Batlle-Bayer et al., 2010). Franco et al. (2015) observed similar or little increase in soil C stocks during the first five years after LUC from pasture to sugarcane plantation. Rossi et al. (2013) reported that the longer the period of time with stalk burning management, the greater are the losses of C stocks. These authors observed that C stocks in soil with 1-year sugarcane plantation were not different from those in soil under pasture at 10-20 and 20-30 cm depths.

The technical potential for soil C accretion in sugarcane fields can create a favorable long-term C budget (Anderson-Teixeira et al., 2009). In a recent review about the effects of sugarcane harvest management on soil C stocks, La Scala Jr et al. (2012) reported that green harvest system (non-burning practice) can sequester as much as 1.87±0.20 Mg C ha^{-1} $year^{-1}$ in topsoil compared with that under the burning practice prior to harvest. However, the simple conversion of sugarcane fields from burned to green harvest system does not guarantee significant increases in soil C stocks over time. Tillage operations in sugarcane may accentuate soil CO_2-C emissions during field preparation, conducted typically every five to six years after planting (La Scala Jr et al., 2006; Silva-Olaya et al., 2013). In a 7-year study, Segnini et al. (2013) isolated the impacts of the maintenance of straw on the soil surface and tillage operations during sugarcane renovation. The authors observed that adoption of green cane and conventional tillage accumulated 0.67 Mg C ha^{-1} $year^{-1}$ compared with 1.63 Mg C ha^{-1} $year^{-1}$ of sequestration under green cane and no-tillage.

The data in Table 3 show a soil C accumulation rate of 0.23 Mg C ha^{-1} $year^{-1}$ in the 0-20 cm layer upon conversion of annual crop into sugarcane. On the contrary, the transitions of coffee and citrus resulted in loss of soil C at the rate of 0.28 and 0.85 Mg C ha^{-1} $year^{-1}$, respectively. Effects of neither of these LUCs (e.g., coffee, citrus and annual crop) to sugarcane were statistically significant ($p < 0.05$) in the 0-20 cm soil layer (Figure 4). Nevertheless, the soil C stocks in the sub-soil may be adversely affected by LUC and agricultural practices. Batlle-Bayer et al. (2010) observed that gains in soil C stock to 1-m depth by no-till were lower than those only computed for the surface layer. Osher et al. (2003) reported that some of the C depleted in the topsoil under a sugarcane plantation was translocated into the sub-soil, and concluded that the loss of C upon land-use conversion can be overestimated if gains in the sub-soil are not considered. Similar discrepancy was observed for conversion of pasture to sugarcane, in which a soil C depletion was significant ($p < 0.05$) only for the 0-20 cm layer (Figure 4). There was no statistically significant difference ($p > 0.05$) in soil C stocks among land uses under pasture and sugarcane established after pasture in 0-100 cm depth. These trends indicate that sub-soil layers can retain more of the antecedent C stocks following the land-use conversion. In this case, soil C was lost at the rate of 2.07 Mg C ha^{-1} year^{-1} in the 0-100 cm layer (Table 3).

Conversion of coffee to sugarcane depleted soil C stock from 124.5 to 97.7 Mg C ha^{-1} (21.5%) in the 0-100 cm layer ($p < 0.05$) at an average rate of 8.95 Mg C ha^{-1} year^{-1} over 3 years since the initial LUC. Similarly, conversion of citrus to sugarcane depleted soil C stock from 147.7 to 112.8 Mg C ha^{-1} (23.6%) in the 0-100 cm layer ($p < 0.05$) at an average rate of 8.74 Mg C ha^{-1} year^{-1} over 4 years (Figure 4; Table 3). Considering an ethanol C offset of 9.8 Mg CO_2 ha^{-1} year^{-1} by substituting fossil fuels (Fargione et al., 2008), this magnitude of soil C debt would take around 10 and 13 years to recover upon conversion of coffee and citrus into sugarcane, respectively.

Higher amounts of root biomass under coffee and citrus, and the absence of soil disturbance in the inter-row over the last 8 and 15 years, are among the principal factors affecting the soil C debts upon conversion into sugarcane, respectively (Table 2). Similar to the deep-rooted grasses, perennial tree crops (e.g., coffee and citrus) also have a deep root system, transfer C into the sub-soil, and it is less prone to oxidation and loss (Fisher et al., 1994).

In contrast to the LUC of coffee and citrus, there was no significant difference in soil C stocks in the 0-100 cm layer when sugarcane followed an annual crop ($p > 0.05$). Conversion of annual crop to sugarcane depleted soil C stock at the rate of 1.23 Mg C ha^{-1} year^{-1} in the 0-100 cm layer (Table 3). However, Mello et al. (2014) reported that conversion of annual cropland to sugarcane increased soil C stocks (0-100 cm) from 126.7 to 148.2 Mg C ha^{-1} (17%) over 20-year, and the increase was observed in 7 of 13 comparison pairs. The apparent contradiction between the results reported herein and those by Mello and colleagues may be attributed to differences in soil type, climate conditions and agricultural practices. In the present study, both land uses (e.g., annual crop and sugarcane converted from annual crop) were under intensive soil tillage in the last years of cultivation. Furthermore, the harvest residues were not returned to the soil in the sugarcane plantation (i.e., converted from annual crop) during the last 4 years (Table 2).

3.3.2 Humification index of SOM (H_{LIFS})

Similar to soil C stocks, assessment of the H_{LIFS} is also important to determining management-induced changes in SOM quality. The data presented in Figure 5 compare the H_{LIFS} of SOM among land uses and soil depths. Each paired comparison being under same soil type and climatic conditions, it is evident that most of the LUC to sugarcane plantation increased H_{LIFS} in the sub-soil, except in the pasture area ($p < 0.05$). Some land uses under sugarcane plantation more than doubled H_{LIFS} for some depths in comparison with the previous land uses ($p < 0.05$). This trend was especially true for conversions of coffee and citrus to sugarcane. Results presented herein are in agreement with those of Rossi et al. (2013), indicating a more intensive decomposition of organic material and a possible accumulation of more recalcitrant C under sugarcane plantation (Rovira and Vallejo, 2002).

Soil under pasture had lower H_{LIFS} in the 0-10 and 10-20 cm layers compared with that under sugarcane established on pasture ($p < 0.05$), and there was no difference in H_{LIFS} in sub-soil ($p > 0.05$) (Figure 5). The absence of soil disturbance during the last 10 years could explain lower H_{LIFS} in the topsoil under pasture (Table 2). The organic matter in soils managed by conventional tillage is more recalcitrant than in those managed with no-tillage, and therefore with higher H_{LIFS} of its SOM (Milori et al., 2006; Dieckow et al., 2009). Higher H_{LIFS} degree was also reported in sugarcane fields under conventional tillage than in soil under no-tillage (Segnini et al., 2013), which indicates that some other protection mechanisms (e.g., physical protection in aggregates) are not effective in protecting the most labile fractions of the organic matter (Milori et al., 2006).

In addition to the conventional soil tillage every 5 years, the adoption of green harvest management (i.e., non-burning practice) in the last 2 years is among the main factors responsible for increasing H_{LIFS} in the land-use under sugarcane established on pasture (Table 2; Figure 5). Panosso et al. (2011) reported a higher H_{LIFS} of SOM in green harvested area compared to that under the burned cane, attributing it to the high input of fresh organic matter on the soil surface which could stimulate the mineralization of stable C present in the humic substances. Segnini et al. (2013) also concluded that the presence of sugarcane straw seemed to be an efficient pathway for restoring soil C stock, in spite of the fact that incorporation of straw under conventional tillage did not improve soil C accumulation and its quality.

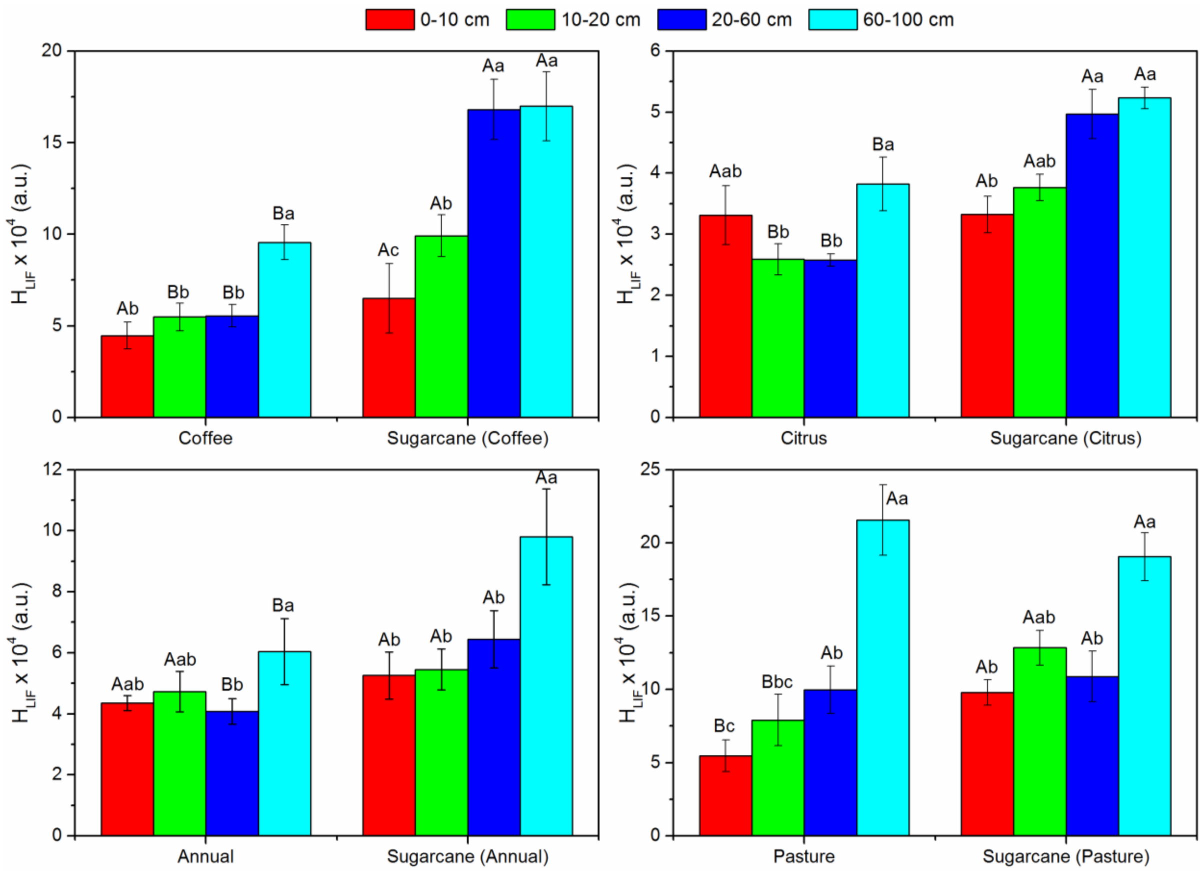

Figure 5. Humification index (H_{LIFS}) of soil organic matter (SOM) obtained by Laser-Induced Fluorescence Spectroscopy for each comparison pair in the different soil layers (0-10, 10-20, 20-60 and 60-100 cm), following the land-use change (LUC) of coffee, citrus, annual crop, and pasture into sugarcane plantation in southern Brazil. Each data represents mean values for five replicates. Mean values followed by different capital letters indicate differences for the same depth among each comparison pair and those followed by different lower case letters indicate difference among all depths for each land-use system (Tukey test: $p < 0.05$).

The data presented in Figure 5 show that land uses under sugarcane and in soil under pasture had a smooth gradient of H_{LIFS}, which increased with soil depth. Total C content decreased with increase in depth (Figure 3), a trend opposite to that of H_{LIFS} with soil depth (Figure 5). Such a trend may be due to the illuviation of humic substances from surface into the sub-soil (Krull et al., 2002), indicating a more humified SOM with soil depth. Additionally, lower H_{LIFS} in the topsoil can be related to the presence of labile C resulting from the constant deposition of fresh organic matter from sugarcane residues (e.g., green harvest regime) and the input of senesced leaves and dead roots in pasture area (Milori et al., 2006), which in turn overwhelm the capacity of microorganisms to decompose them (Segnini et al, 2013).

Fontaine et al. (2007) reported that the stability of organic C is maintained with the absence of fresh organic C in sub-soil, which is an essential source of energy for soil microbes. In these circumstances, there is further decomposition of humic substances by microorganisms (Segnini et al., 2011). For the most sugarcane being harvested with green cane system, the loss of ancient buried C would be escalated by any change in land-use and agricultural practice that increases the distribution of fresh C along the soil profile (Fontaine et al., 2007). Most of the LUC (especially coffee, citrus and pasture) to sugarcane plantation are depleting soil C stock, which corroborates with humification degree observed herein. Then, it is evident that the current management of sugarcane plantation in those paired plots is not contributing to incorporate C and fresh organic matter throughout the soil profile.

3.4 Conclusion

The impacts of the LUC due to sugarcane expansion is important to soil C stocks, which could reduce the C offset by sugarcane ethanol for fossil fuels depending on the type of land-use transition. The data presented show that the LUC of coffee and citrus to sugarcane depleted SOC pool by 21.5% (26.8 Mg C ha^{-1}) and 23.6% (34.9 Mg C ha^{-1}) in the 0-100 cm layer after a period of 3 and 4 years, respectively. There was no difference in soil C stocks in the 0-100 cm layer upon conversion of annual crop and pasture into sugarcane. In contrast, only the conversion of pastureland into sugarcane decreased soil C stock in 0-20 cm depth, with depletion of 13.3 Mg C ha^{-1} (43.9%) over 8 years following such transition.

The data of Laser-Induced Fluorescence Spectroscopy (LIFS) showed that the higher the losses of soil C, the greater was the humification index (H_{LIFS}). The magnitude of LIFS also indicated that sugarcane plantation increased H_{LIFS} for all evaluated pairs in comparison with that under the previous land uses, especially due to the adoption of conventional tillage and the maintenance of sugarcane straw on the soil surface. Most of the LUC to sugarcane plantation increased H_{LIFS} in the sub-soil, except in pasture area, which had lower H_{LIFS} compared to that under sugarcane (pasture) in the surface layers of soil. Furthermore, land-use under pasture and in soils under sugarcane had a smooth gradient of H_{LIFS}, which increased with soil depth. Therefore, factors controlling the quantity and quality of SOM, influenced by any change in land-use and agricultural practice, are important limitations that should be considered for assessing the sustainability of sugarcane-based ethanol.

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CHAPTER 4 – FINAL REMARKS

Sugarcane-based ethanol can play an important role in mitigation of greenhouse gas (GHG) emission by replacing fossil fuels. However, it should be paid attention to the expansion of sugarcane plantation areas, as this could result in additional GHG emissions, especially when there are significant losses in biomass and soil carbon (C) pools. Despite the high level of uncertainty by applying IPCC methodologies on those estimates, inventorying GHG emissions in agricultural areas is imperative to derive regional-to-national scale estimates, and to support policies and management decisions regarding the sugarcane ethanol towards a greater sustainability.

The data obtained in Chapter 2 pointed to an increase in C reservoirs (i.e., biomass and soil) upon conversion of annual crops and pasture to sugarcane, and a decrease of C reservoirs when citrus, forest plantation and native vegetation are converted into sugarcane. As most of the pasture land in Brazil is somehow degraded, and the LUC-induced debt of soil C stock depends on the status of degradation and conditions of soil management, establishing sugarcane plantation on degraded lands with simultaneous pasture intensification should be a key priority.

Our estimates also pointed that the expansion of sugarcane plantation contributed for reducing GHG emissions (57%) associated with agricultural production during 2006-2011 in south-central Brazil. Even presenting an accumulated GHG emission of 217.1 Tg CO_2eq by 2030, the C savings attributed to sugarcane-based ethanol use in substitution of fossil fuels would be enough to offset such emission.

The data of field experiments in Chapter 3 indicated that conversion of perennial tree crops (e.g., coffee and citrus) to sugarcane depleted soil C stock in 0-100 cm depth. In contrast, there was no difference in 0-100 cm depth upon conversion of annual crops into sugarcane. The results presented herein reinforce that an assessment of soil C stock in sub-soil seemed to attenuate the effects of LUC in soil C depletion. This trend was especially true for conversion of pasture into sugarcane, in which significant differences were observed only in 0-20 cm depth.

The LUC-induced depletion of soil C stock may be attributed to the intrinsic management of soil for each land use. There was a trend for accretion of soil C stock when the intensity of soil disturbance decreased, as observed in areas under perennial cultivation (e.g., coffee, citrus and pasture), semi-perennial cultivation (sugarcane), and annual cultivation (annual crops), respectively. This evidence, however, deserves further investigation due to the uncertainty derived from complexity of soil C dynamics after the LUC.

There is a need of additional research that should be focused on improving estimates of GHG emission based on field data, in order to reduce the overall uncertainty of the results derived through a life cycle approach. The GHG balance from cultivation and direct land use change of recently established sugarcane plantation was calculated using simplified methods based on default emissions factors for all C pools and agricultural inputs. Although straightforward, the IPCC default method is subjected to debate given that it may not capture local variations accurately. Similarly, this study deals with complex and integrated information (e.g., data from remote sensing and agricultural inputs) consisting of several parameters, which have many sources of uncertainty that may affect the accuracy of the results. Uncertainties can be associated to insufficient knowledge and/or oversimplification of systems, mechanisms or parameters. New studies would benefit from an uncertainty analysis that this approach carries, and a discussion of the significance of that uncertainty.

APPENDICES

APPENDIX A – Expanded sugarcane areas (in hectare) according to five types of land use prior to sugarcane (*agriculture, pasture, citrus, plantation forest and natural forest*) during the period of 2006 until 2011 in the south-central region of Brazil.

States	Crop/ Class	2006 ha	2006 %	2007 ha	2007 %	2008 ha	2008 %	2009 ha	2009 %
GO	Agriculture	21,027.61	51.56	41,312.77	48.29	83,994.84	58.67	44,333.77	32.80
	Pasture	19,663.40	48.22	43,500.86	50.84	58,633.41	40.96	90,469.43	66.94
	Citrus	60.83	0.15	0.00	0.00	0.00	0.00	0.00	0.00
	Plantation forest	0.00	0.00	29.47	0.03	19.66	0.01	0.00	0.00
	Natural forest	28.16	0.07	714.81	0.84	509.09	0.36	343.76	0.25
	Total	40,780.00	100.00	85,559.00	100.00	143,157.00	100.00	135,148.00	100.00
MT	Agriculture	5,372.23	20.11	2,980.97	11.68	8,734.83	28.42	3,890.00	22.14
	Pasture	21,163.51	79.24	21,062.81	82.52	21,440.88	69.76	13,521.85	76.97
	Citrus	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Plantation forest	0.00	0.00	57.86	0.23	23.85	0.08	0.00	0.00
	Natural forest	173.26	0.65	1,422.36	5.57	538.36	1.75	157.06	0.89
	Total	26,709.00	100.00	25,524.00	100.00	30,737.00	100.00	17,568.00	100.00
MS	Agriculture	6,651.67	25.90	21,283.09	45.82	26,564.82	30.38	32,257.02	26.53
	Pasture	19,033.18	74.10	23,948.56	51.56	60,708.24	69.43	89,281.66	73.43
	Citrus	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Plantation forest	0.00	0.00	109.75	0.24	0.00	0.00	17.12	0.01
	Natural forest	0.00	0.00	1,103.58	2.38	161.96	0.19	31.21	0.03
	Total	25,686.00	100.00	46,446.00	100.00	87,434.00	100.00	121,587.00	100.00
MG	Agriculture	27,429.51	42.61	56,815.33	47.23	57,995.83	41.08	20,180.58	20.96
	Pasture	36,353.71	56.48	61,566.36	51.17	81,562.49	57.77	75,760.61	78.69
	Citrus	124.31	0.19	1,030.28	0.86	736.46	0.52	212.92	0.22
	Plantation forest	312.49	0.49	195.99	0.16	215.10	0.15	28.66	0.03
	Natural forest	145.98	0.23	700.13	0.58	680.12	0.48	97.25	0.10
	Total	64,366.00	100.00	120,306.00	100.00	141,190.00	100.00	96,279.00	100.00
PR	Agriculture	21,921.69	33.18	34,182.00	31.84	27,692.04	28.34	5,457.82	15.35
	Pasture	43,989.72	66.58	72,874.89	67.89	69,926.12	71.56	30,083.60	84.59
	Citrus	0.00	0.00	23.71	0.02	0.00	0.00	0.00	0.00
	Plantation forest	108.57	0.16	21.55	0.02	12.46	0.01	23.58	0.07
	Natural forest	47.20	0.07	248.93	0.23	92.39	0.09	0.00	0.00
	Total	66,066.00	100.00	107,350.00	100.00	97,723.00	100.00	35,565.00	100.00
SP	Agriculture	92,082.74	30.13	259,647.73	40.77	225,579.87	34.08	84,872.57	26.37
	Pasture	193,790.30	63.41	362,329.86	56.90	413,783.63	62.52	227,706.05	70.76
	Citrus	18,736.27	6.13	12,875.14	2.02	21,169.04	3.20	8,389.64	2.61
	Plantation forest	340.81	0.11	827.64	0.13	224.25	0.03	69.23	0.02
	Natural forest	652.87	0.21	1,134.63	0.18	1,116.19	0.17	763.51	0.24
	Total	305,603.00	100.00	636,814.00	100.00	661,874.00	100.00	321,801.00	100.00
South Central	Agriculture	174,485.45	32.97	416,221.89	40.73	430,562.23	37.05	190,991.75	26.24
	Pasture	333,993.80	63.11	585,283.34	57.27	706,054.77	60.76	526,823.21	72.37
	Citrus	18,921.42	3.58	13,929.13	1.36	21,905.50	1.88	8,602.56	1.18
	Plantation forest	761.87	0.14	1,242.27	0.12	495.31	0.04	138.58	0.02
	Natural forest	1,047.48	0.20	5,324.43	0.52	3,098.11	0.27	1,392.80	0.19
	Total	529,210.02	100.00	1,022,001.07	100.00	1,162,115.92	100.00	727,948.90	100.00

APPENDIX A (continued) – Expanded sugarcane areas (in hectare) according to five types of land use prior to sugarcane (*agriculture, pasture, citrus, plantation forest and natural forest*) during the period of 2006 until 2011 in the south-central region of Brazil.

States	Crop/ Class	2010		2011		Total	
		ha	%	ha	%	ha	%
	Agriculture	34,358.26	42.85	32,022.94	37.69	257,050.18	45.11
	Pasture	45,606.81	56.87	52,576.26	61.89	310,450.16	54.49
	Citrus	0.00	0.00	0.00	0.00	60.83	0.01
	Plantation forest	0.00	0.00	0.00	0.00	49.13	0.01
	Natural forest	222.86	0.28	354.81	0.42	2,173.49	0.38
GO	**Total**	80,189.00	100.00	84,954.00	100.00	569,787.00	13.39
	Agriculture	3,187.53	24.95	2,933.30	17.27	27,098.87	20.80
	Pasture	9,320.79	72.95	13,297.02	78.28	99,806.86	76.60
	Citrus	0.00	0.00	0.00	0.00	0.00	0.00
	Plantation forest	0.00	0.00	0.00	0.00	81.71	0.06
	Natural forest	267.60	2.09	756.68	4.45	3,315.32	2.54
MT	**Total**	12,777.00	100.00	16,987.00	100.00	130,302.00	3.06
	Agriculture	10,903.24	13.20	15,936.92	21.01	113,596.75	25.84
	Pasture	71,522.39	86.57	59,187.41	78.04	323,681.44	73.63
	Citrus	0.00	0.00	0.00	0.00	0.00	0.00
	Plantation forest	14.47	0.02	1.02	0.00	142.36	0.03
	Natural forest	179.89	0.22	719.67	0.95	2,196.31	0.50
MS	**Total**	82,620.00	100.00	75,844.00	100.00	439,617.00	10.33
	Agriculture	23,443.22	37.89	23,240.99	32.47	209,105.46	37.64
	Pasture	38,098.53	61.57	48,211.78	67.36	341,553.49	61.48
	Citrus	89.03	0.14	11.39	0.02	2,204.39	0.40
	Plantation forest	0.00	0.00	17.60	0.02	769.84	0.14
	Natural forest	246.22	0.40	95.24	0.13	1,964.93	0.35
MG	**Total**	61,877.00	100.00	71,577.00	100.00	555,595.00	13.06
	Agriculture	3,127.62	19.52	3,900.53	22.68	96,281.69	28.32
	Pasture	12,859.96	80.26	13,248.63	77.04	242,982.92	71.48
	Citrus	0.00	0.00	46.84	0.27	70.55	0.02
	Plantation forest	0.00	0.00	0.00	0.00	166.16	0.05
	Natural forest	34.24	0.21	0.00	0.00	422.76	0.12
PR	**Total**	16,023.00	100.00	17,196.00	100.00	339,923.00	7.99
	Agriculture	29,037.32	21.13	36,631.97	23.42	727,852.20	32.79
	Pasture	99,536.58	72.42	102,911.14	65.78	1,400,057.56	63.07
	Citrus	8,544.31	6.22	15,757.76	10.07	85,472.16	3.85
	Plantation forest	270.74	0.20	1,053.78	0.67	2,786.47	0.13
	Natural forest	54.99	0.04	82.34	0.05	3,804.54	0.17
SP	**Total**	137,445.00	100.00	156,437.00	100.00	2,219,974.00	52.17
	Agriculture	104,057.19	26.62	114,666.66	27.11	1,430,985.16	33.63
	Pasture	276,945.06	70.84	289,432.24	68.42	2,718,532.42	63.89
	Citrus	8,633.34	2.21	15,815.99	3.74	87,807.94	2.06
	Plantation forest	285.22	0.07	1,072.40	0.25	3,995.66	0.09
	Natural forest	1,005.80	0.26	2,008.73	0.47	13,877.36	0.33
South Central	**Total**	390,926.61	100.00	422,996.02	100.00	4,255,198.54	100.00

APPENDIX B – Sugarcane cultivated areas (in hectare) during the period of 2006 until 2011, according to each phase of its agricultural production (*expansion, renovated, ratoon maintenance and harvest*) in south-central Brazil.

States	Crop season	Planting [a]		Ratoon maintenance [b]		Total area [a+b] (ha)
		Expansion (ha)	Renovated* (ha)	GH** (ha)	BH*** (ha)	
	2006	40,780	10,407	72,038	106,292	229,517
	2007	85,559	14,407	116,469	96,406	312,841
	2008	143,157	16,395	171,479	102,960	433,991
	2009	135,148	19,130	275,986	129,324	559,588
	2010	80,189	14,616	394,421	136,913	626,139
GO	2011	84,954	23,914	492,879	104,295	706,042
	2006	26,709	18,127	86,869	69,485	201,190
	2007	25,524	18,000	108,548	65,566	217,638
	2008	30,737	26,112	126,013	56,309	239,171
	2009	17,568	7,443	164,436	56,158	245,605
	2010	12,777	12,158	174,646	57,550	257,131
MT	2011	16,987	22,977	184,220	38,154	262,338
	2006	25,686	12,484	35,855	94,489	168,514
	2007	46,446	13,035	43,863	109,758	213,102
	2008	87,434	13,315	94,393	96,129	291,271
	2009	121,587	6,227	156,447	123,835	408,096
	2010	82,620	9,178	255,854	141,549	489,201
MS	2011	75,844	11,077	357,263	108,347	552,531
	2006	64,366	15,705	104,036	166,133	350,240
	2007	120,306	17,838	151,104	175,853	465,101
	2008	141,190	29,990	252,529	163,438	587,147
	2009	96,279	25,409	346,447	192,960	661,095
	2010	61,877	25,873	457,235	181,825	726,810
MG	2011	71,577	39,453	542,477	136,413	789,920
	2006	66,066	14,747	61,619	277,330	419,762
	2007	107,350	25,058	195,932	195,932	524,272
	2008	97,723	23,154	117,125	365,029	603,031
	2009	35,565	19,417	162,805	410,410	628,197
	2010	16,023	21,018	173,517	421,198	631,756
PR	2011	17,196	24,307	181,149	410,138	632,790
	2006	305,603	284,390	1,127,983	1,626,276	3,344,252
	2007	636,814	276,992	1,330,322	1,710,403	3,954,531
	2008	661,874	385,941	1,837,641	1,668,770	4,554,226
	2009	321,801	289,860	2,513,297	1,676,739	4,801,697
	2010	137,445	259,265	2,976,282	1,592,872	4,965,864
SP	2011	156,437	462,179	3,325,224	1,128,138	5,071,978
	2006	529,210	355,860	1,488,401	2,340,004	4,713,475
	2007	1,021,999	365,330	1,946,238	2,353,918	5,687,485
	2008	1,162,115	494,907	2,599,181	2,452,634	6,708,837
	2009	727,948	367,486	3,619,417	2,589,427	7,304,278
SOUTH	2010	390,931	342,108	4,431,954	2,531,908	7,696,901
CENTRAL	2011	422,995	583,907	5,083,213	1,925,484	8,015,599

Source: Authors' personal data and CANASAT project (http://www.dsr.inpe.br/laf/canasat) - National Institute for Space Research (INPE). * Represented by the sugarcane areas which were renovated in the current crop season; ** Ratoon maintenance BH: sugarcane areas which were harvested with burning during the pre-harvest (BH) in the current crop season; *** Ratoon maintenance GH: sugarcane areas which were harvested under non-burning practice (GH; green cane management) in the current crop season.

APPENDIX B (continued) – Sugarcane cultivated areas (in hectare) during the period of 2006 until 2011, according to each phase of its agricultural production (*expansion, renovated, ratoon maintenance and harvest*) in south-central Brazil.

States	Crop season	Harvest			
		GH (ha)	**%**	**BH (ha)**	**%**
	2006	95,596	40.4	141,051	59.6
	2007	167,724	54.7	138,832	45.3
	2008	262,770	62.5	157,772	37.5
	2009	358,808	68.1	168,135	31.9
	2010	467,690	74.2	162,347	25.8
GO	2011	574,563	82.5	121,580	17.5
	2006	107,816	55.6	86,241	44.4
	2007	135,476	62.3	81,832	37.7
	2008	159,516	69.1	71,280	30.9
	2009	186,228	74.5	63,600	25.5
	2010	189,752	75.2	62,528	24.8
MT	2011	208,288	82.8	43,139	17.2
	2006	44,650	27.5	117,665	72.5
	2007	58,291	28.6	145,860	71.4
	2008	126,193	49.5	128,513	50.5
	2009	179,284	55.8	141,912	44.2
	2010	302,665	64.4	167,447	35.6
MS	2011	418,036	76.7	126,777	23.3
	2006	132,066	38.5	210,893	61.5
	2007	211,923	46.2	246,633	53.8
	2008	344,696	60.7	223,088	39.3
	2009	400,278	64.2	222,942	35.8
	2010	517,614	71.5	205,836	28.5
MG	2011	618,566	79.9	155,546	20.1
	2006	73,103	18.2	329,013	81.8
	2007	171,320	50.0	171,320	50.0
	2008	118,580	24.3	369,562	75.7
	2009	154,742	28.4	390,086	71.6
	2010	179,997	29.2	436,929	70.8
PR	2011	190,437	30.6	431,165	69.4
	2006	1,350,329	41.0	1,946,843	59.0
	2007	1,675,337	43.8	2,153,991	56.2
	2008	2,177,698	52.4	1,977,577	47.6
	2009	2,578,626	60.0	1,720,323	40.0
	2010	3,237,090	65.1	1,732,453	34.9
SP	2011	3,624,989	74.7	1,229,839	25.3
	2006	1,803,559	38.9	2,831,707	61.1
	2007	2,420,072	45.2	2,938,468	54.8
	2008	3,189,452	52.1	2,927,793	47.9
	2009	3,857,967	58.8	2,706,998	41.2
SOUTH	2010	4,894,809	63.9	2,767,540	36.1
CENTRAL	2011	5,634,878	72.8	2,108,045	27.2

Source: Authors' personal data and CANASAT project (http://www.dsr.inpe.br/laf/canasat) - National Institute for Space Research (INPE).

APPENDIX C – GHG emissions from sugarcane cultivation (in Tg CO_2eq) during the period of 2006 until 2011, according to each state in south-central Brazil.

States	Agricultural phase	Crop season – GHG emissions from sugarcane cultivation (in Tg CO_2eq)						Total
		2006	2007	2008	2009	2010	2011	
	Renovated	0.02	0.03	0.03	0.03	0.03	0.04	0.17
	Expansion	0.07	0.15	0.25	0.24	0.14	0.15	0.99
	R. Maintenance (GH)	0.12	0.20	0.29	0.47	0.67	0.84	2.61
	R. Maintenance (BH)	0.15	0.13	0.14	0.18	0.19	0.14	0.93
	Green Harvest (GH)	0.08	0.13	0.21	0.28	0.37	0.45	1.52
	Burned Harvest (BH)	0.17	0.17	0.19	0.20	0.19	0.14	1.06
GO	**Total**	0.60	0.80	1.11	1.40	1.59	1.77	7.28
	Renovated	0.03	0.03	0.05	0.01	0.02	0.04	0.18
	Expansion	0.05	0.04	0.05	0.03	0.02	0.03	0.23
	R. Maintenance (GH)	0.15	0.19	0.22	0.28	0.30	0.32	1.45
	R. Maintenance (BH)	0.10	0.09	0.08	0.08	0.08	0.05	0.47
	Green Harvest (GH)	0.08	0.11	0.13	0.15	0.15	0.16	0.78
	Burned Harvest (BH)	0.10	0.10	0.08	0.08	0.07	0.05	0.49
MT	**Total**	0.51	0.56	0.60	0.62	0.65	0.65	3.59
	Renovated	0.02	0.02	0.02	0.01	0.02	0.02	0.11
	Expansion	0.04	0.08	0.15	0.21	0.14	0.13	0.77
	R. Maintenance (GH)	0.06	0.08	0.16	0.27	0.44	0.61	1.61
	R. Maintenance (BH)	0.13	0.15	0.13	0.17	0.19	0.15	0.93
	Green Harvest (GH)	0.04	0.05	0.10	0.14	0.24	0.33	0.89
	Burned Harvest (BH)	0.14	0.17	0.15	0.17	0.20	0.15	0.99
MS	**Total**	0.43	0.55	0.72	0.97	1.23	1.39	5.30
	Renovated	0.03	0.03	0.05	0.04	0.05	0.07	0.27
	Expansion	0.11	0.21	0.25	0.17	0.11	0.12	0.97
	R. Maintenance (GH)	0.18	0.26	0.43	0.59	0.78	0.93	3.17
	R. Maintenance (BH)	0.23	0.24	0.22	0.26	0.25	0.19	1.40
	Green Harvest (GH)	0.10	0.17	0.27	0.32	0.41	0.49	1.75
	Burned Harvest (BH)	0.25	0.29	0.27	0.27	0.25	0.19	1.51
MG	**Total**	0.90	1.20	1.49	1.65	1.84	1.98	9.07
	Renovated	0.03	0.04	0.04	0.03	0.04	0.04	0.22
	Expansion	0.12	0.19	0.17	0.06	0.03	0.03	0.59
	R. Maintenance (GH)	0.11	0.34	0.20	0.28	0.30	0.31	1.53
	R. Maintenance (BH)	0.38	0.27	0.50	0.56	0.58	0.56	2.86
	Green Harvest (GH)	0.06	0.14	0.09	0.12	0.14	0.15	0.70
	Burned Harvest (BH)	0.39	0.20	0.44	0.46	0.52	0.51	2.54
PR	**Total**	1.08	1.17	1.45	1.52	1.60	1.61	8.43
	Renovated	0.50	0.48	0.67	0.51	0.45	0.81	3.41
	Expansion	0.53	1.11	1.15	0.56	0.24	0.27	3.87
SP	R. Maintenance (GH)	1.93	2.28	3.14	4.30	5.09	5.69	22.43

	R. Maintenance (BH)	2.23	2.35	2.29	2.30	2.19	1.55	12.91
	Green Harvest (GH)	1.06	1.32	1.72	2.03	2.55	2.86	11.54
	Burned Harvest (BH)	2.32	2.57	2.36	2.05	2.06	1.47	12.82
	Total	8.58	10.10	11.33	11.75	12.59	12.64	66.99
SOUTH CENTRAL	Renovated	0.62	0.64	0.86	0.64	0.60	1.02	4.37
	Expansion	0.92	1.78	2.03	1.27	0.68	0.74	7.42
	R. Maintenance (GH)	2.55	3.33	4.45	6.19	7.58	8.70	32.79
	R. Maintenance (BH)	3.21	3.23	3.37	3.56	3.48	2.64	19.49
	Green Harvest (GH)	1.42	1.91	2.51	3.04	3.86	4.44	17.19
	Burned Harvest (BH)	3.37	3.50	3.49	3.23	3.30	2.51	19.40
	Total	12.10	14.39	16.71	17.92	19.49	20.05	100.66

APPENDIX D – Variations in biomass C stocks (in Tg CO_2) through dLUC of recently established sugarcane plantation in south-central Brazil.

States	Previous land use	Crop season – biomass C changes (in Tg CO_2)						Total
		2006	2007	2008	2009	2010	2011	
	Agriculture	-1.14	-2.24	-4.56	-2.41	-1.86	-1.74	-13.95
	Pasture	-1.44	-3.19	-4.30	-6.63	-3.34	-3.86	-22.77
	Citrus	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Plantation forest	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Natural forest	0.00	0.07	0.05	0.03	0.02	0.03	0.21
GO	**Total**	-2.58	-5.36	-8.81	-9.01	-5.19	-5.56	-36.50
	Agriculture	-0.29	-0.16	-0.47	-0.21	-0.17	-0.16	-1.47
	Pasture	-1.55	-1.54	-1.57	-0.99	-0.68	-0.98	-7.32
	Citrus	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Plantation forest	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Natural forest	0.02	0.14	0.05	0.02	0.03	0.07	0.33
MT	**Total**	-1.83	-1.56	-1.99	-1.19	-0.83	-1.06	-8.46
	Agriculture	-0.36	-1.15	-1.44	-1.75	-0.59	-0.86	-6.16
	Pasture	-1.40	-1.76	-4.45	-6.55	-5.24	-4.34	-23.74
	Citrus	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Plantation forest	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Natural forest	0.00	0.11	0.02	0.00	0.02	0.07	0.22
MS	**Total**	-1.76	-2.80	-5.88	-8.29	-5.82	-5.13	-29.68
	Agriculture	-1.49	-3.08	-3.15	-1.10	-1.27	-1.26	-11.35
	Pasture	-2.67	-4.51	-5.98	-5.56	-2.79	-3.54	-25.05
	Citrus	0.00	0.01	0.01	0.00	0.00	0.00	0.03
	Plantation forest	0.01	0.01	0.01	0.00	0.00	0.00	0.02
	Natural forest	0.01	0.07	0.07	0.01	0.02	0.01	0.19
MG	**Total**	-4.13	-7.51	-9.05	-6.64	-4.04	-4.79	-36.15
	Agriculture	-1.19	-1.85	-1.50	-0.30	-0.17	-0.21	-5.22
	Pasture	-3.23	-5.34	-5.13	-2.21	-0.94	-0.97	-17.82
	Citrus	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Plantation forest	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Natural forest	0.00	0.02	0.01	0.00	0.00	0.00	0.04
PR	**Total**	-4.41	-7.17	-6.62	-2.50	-1.11	-1.18	-23.00
	Agriculture	-5.00	-14.09	-12.24	-4.61	-1.58	-1.99	-39.50
	Pasture	-14.21	-26.57	-30.34	-16.70	-7.30	-7.55	-102.67
	Citrus	0.22	0.15	0.25	0.10	0.10	0.18	1.00
	Plantation forest	0.01	0.02	0.01	0.00	0.01	0.03	0.08
	Natural forest	0.06	0.11	0.11	0.08	0.01	0.01	0.37
SP	**Total**	-18.91	-40.37	-42.22	-21.13	-8.76	-9.31	-140.71
	Agriculture	-9.47	-22.59	-23.37	-10.36	-5.65	-6.22	-77.65
	Pasture	-24.49	-42.92	-51.78	-38.63	-20.31	-21.23	-199.36
	Citrus	0.22	0.16	0.26	0.10	0.10	0.19	1.03
	Plantation forest	0.02	0.04	0.01	0.00	0.01	0.03	0.12
	Natural forest	0.10	0.52	0.30	0.14	0.10	0.20	1.36
SOUTH CENTRAL	**Total**	-33.61	-64.78	-74.57	-48.76	-25.75	-27.03	-274.50

APPENDIX E – Changes in soil C stocks and its N_2O emissions from SOM mineralization after a 20-year period (in Tg CO_2eq) associated to dLUC of recently established sugarcane plantation in south-central Brazil.

States	Previous land use	Crop season – Soil C changes and its N_2O emissions from SOM mineralization (in Tg CO_2eq)				
		2006	2007	2008	2009	2010
	Agriculture	-0.038	-0.152	-0.418	-0.765	-1.174
	Pasture	0.022	0.091	0.224	0.456	0.738
	Citrus	0.000	0.000	0.000	0.000	0.000
	Plantation forest	0.000	0.000	0.000	0.000	0.000
	Natural forest	0.000	0.003	0.008	0.015	0.022
GO	**Total**	-0.017	-0.058	-0.185	-0.293	-0.413
	Agriculture	-0.010	-0.025	-0.056	-0.094	-0.138
	Pasture	0.023	0.069	0.139	0.223	0.318
	Citrus	0.000	0.000	0.000	0.000	0.000
	Plantation forest	0.000	0.000	0.000	0.000	0.000
	Natural forest	0.001	0.007	0.016	0.025	0.036
MT	**Total**	0.014	0.052	0.099	0.155	0.216
	Agriculture	-0.012	-0.063	-0.162	-0.320	-0.497
	Pasture	0.021	0.068	0.181	0.392	0.682
	Citrus	0.000	0.000	0.000	0.000	0.000
	Plantation forest	0.000	0.000	0.000	0.000	0.000
	Natural forest	0.000	0.004	0.010	0.015	0.021
MS	**Total**	0.009	0.010	0.029	0.088	0.206
	Agriculture	-0.050	-0.203	-0.462	-0.757	-1.095
	Pasture	0.040	0.147	0.343	0.622	0.943
	Citrus	0.000	0.001	0.003	0.004	0.006
	Plantation forest	0.000	0.001	0.001	0.002	0.002
	Natural forest	0.001	0.004	0.010	0.017	0.024
MG	**Total**	-0.009	-0.050	-0.105	-0.112	-0.119
	Agriculture	-0.040	-0.142	-0.294	-0.457	-0.625
	Pasture	0.048	0.176	0.380	0.618	0.869
	Citrus	0.000	0.000	0.000	0.000	0.000
	Plantation forest	0.000	0.000	0.000	0.000	0.001
	Natural forest	0.000	0.001	0.003	0.005	0.006
PR	**Total**	0.009	0.036	0.089	0.166	0.251
	Agriculture	-0.167	-0.807	-1.857	-3.061	-4.318
	Pasture	0.212	0.820	1.881	3.191	4.610
	Citrus	0.015	0.041	0.084	0.134	0.191
	Plantation forest	0.000	0.001	0.002	0.003	0.005
	Natural forest	0.003	0.010	0.022	0.037	0.052
SP	**Total**	0.063	0.065	0.132	0.304	0.539
	Agriculture	-0.317	-1.392	-3.249	-5.454	-7.848
	Pasture	0.365	1.371	3.149	5.503	8.160
	Citrus	0.015	0.042	0.087	0.139	0.197
	Plantation forest	0.001	0.002	0.004	0.006	0.008
	Natural forest	0.004	0.030	0.069	0.113	0.161
SOUTH CENTRAL	**Total**	0.068	0.054	0.060	0.307	0.680

APPENDIX E (continued) – Changes in soil C stocks and its N_2O emissions from SOM mineralization after a 20-year period (in Tg CO_2eq) associated to dLUC of recently established sugarcane plantation in south-central Brazil.

States	Previous land use	Crop season – Soil C changes and its N_2O emissions from SOM mineralization (in Tg CO_2eq)				
		2011	2015	2020	2025	2030
	Agriculture	-1.641	-3.511	-5.849	-8.186	-9.350
	Pasture	1.078	2.436	4.134	5.832	6.792
	Citrus	0.000	0.000	0.001	0.001	0.001
	Plantation forest	0.000	0.000	0.001	0.001	0.001
	Natural forest	0.031	0.066	0.111	0.155	0.177
GO	**Total**	-0.532	-1.008	-1.603	-2.197	-2.379
	Agriculture	-0.187	-0.385	-0.631	-0.877	-0.986
	Pasture	0.427	0.864	1.410	1.956	2.184
	Citrus	0.000	0.000	0.000	0.000	0.000
	Plantation forest	0.000	0.001	0.001	0.001	0.001
	Natural forest	0.049	0.103	0.171	0.238	0.270
MT	**Total**	0.289	0.583	0.950	1.318	1.469
	Agriculture	-0.704	-1.530	-2.563	-3.596	-4.132
	Pasture	1.036	2.452	4.222	5.993	7.081
	Citrus	0.000	0.000	0.000	0.000	0.000
	Plantation forest	0.000	0.001	0.001	0.002	0.002
	Natural forest	0.030	0.066	0.110	0.155	0.179
MS	**Total**	0.362	0.988	1.771	2.553	3.131
	Agriculture	-1.475	-2.997	-4.898	-6.800	-7.606
	Pasture	1.317	2.811	4.680	6.548	7.472
	Citrus	0.008	0.015	0.024	0.033	0.036
	Plantation forest	0.003	0.005	0.008	0.011	0.012
	Natural forest	0.032	0.064	0.104	0.144	0.160
MG	**Total**	-0.115	-0.100	-0.082	-0.063	0.075
	Agriculture	-0.800	-1.500	-2.376	-3.251	-3.502
	Pasture	1.135	2.198	3.527	4.856	5.316
	Citrus	0.000	0.000	0.001	0.001	0.001
	Plantation forest	0.001	0.001	0.002	0.003	0.003
	Natural forest	0.008	0.015	0.023	0.032	0.034
PR	**Total**	0.344	0.714	1.177	1.640	1.852
	Agriculture	-5.642	-10.937	-17.556	-24.174	-26.474
	Pasture	6.142	12.268	19.925	27.583	30.630
	Citrus	0.261	0.539	0.888	1.237	1.394
	Plantation forest	0.007	0.016	0.027	0.037	0.044
	Natural forest	0.067	0.129	0.207	0.284	0.310
SP	**Total**	0.834	2.015	3.491	4.967	5.903
	Agriculture	-10.450	-20.860	-33.872	-46.885	-52.050
	Pasture	11.134	23.029	37.898	52.767	59.475
	Citrus	0.269	0.555	0.914	1.272	1.433
	Plantation forest	0.012	0.024	0.040	0.055	0.062
	Natural forest	0.218	0.444	0.726	1.009	1.130
SOUTH CENTRAL	**Total**	1.182	3.192	5.705	8.217	10.050

APPENDIX F – Accumulated GHG balance (in Tg CO_2eq) by the year 2030, due to dLUC and sugarcane cultivation during the years of 2006 to 2011 in south-central Brazil.

States	Evaluated criteria	Accumulated GHG balance (in Tg CO_2eq)												
		2006	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
	Sugarcane production	0.60	1.41	2.51	3.92	5.51	7.28	9.05	10.83	12.60	14.38	16.15	17.92	19.70
	Δ Soil C stock and N_2O emissions	-0.02	-0.06	-0.19	-0.29	-0.41	-0.53	-0.65	-0.77	-0.89	-1.01	-1.13	-1.25	-1.36
	Δ Biomass C stock	-2.58	-7.94	-16.75	-25.75	-30.94	-36.50	-36.50	-36.50	-36.50	-36.50	-36.50	-36.50	-36.50
GO	**Total**	-1.99	-6.59	-14.42	-22.13	-25.85	-29.75	-28.10	-26.44	-24.79	-23.13	-21.48	-19.82	-18.17
	Sugarcane production	0.51	1.07	1.67	2.29	2.94	3.59	4.24	4.90	5.55	6.20	6.86	7.51	8.16
	Δ Soil C stock and N_2O emissions	0.01	0.05	0.10	0.15	0.22	0.29	0.36	0.44	0.51	0.58	0.66	0.73	0.80
	Δ Biomass C stock	-1.83	-3.39	-5.38	-6.57	-7.40	-8.46	-8.46	-8.46	-8.46	-8.46	-8.46	-8.46	-8.46
MT	**Total**	-1.30	-2.27	-3.62	-4.12	-4.25	-4.58	-3.85	-3.13	-2.40	-1.68	-0.95	-0.22	0.50
	Sugarcane production	0.43	0.98	1.70	2.67	3.91	5.30	6.69	8.08	9.47	10.87	12.26	13.65	15.04
	Δ Soil C stock and N_2O emissions	0.01	0.01	0.03	0.09	0.21	0.36	0.52	0.68	0.83	0.99	1.14	1.30	1.46
	Δ Biomass C stock	-1.76	-4.56	-10.43	-18.73	-24.55	-29.68	-29.68	-29.68	-29.68	-29.68	-29.68	-29.68	-29.68
MS	**Total**	-1.31	-3.56	-8.70	-15.97	-20.44	-24.02	-22.47	-20.92	-19.38	-17.83	-16.28	-14.73	-13.18
	Sugarcane production	0.90	2.10	3.60	5.25	7.08	9.07	11.05	13.03	15.01	16.99	18.98	20.96	22.94
	Δ Soil C stock and N_2O emissions	-0.01	-0.05	-0.10	-0.11	-0.12	-0.12	-0.11	-0.11	-0.10	-0.10	-0.10	-0.09	-0.09
	Δ Biomass C stock	-4.13	-11.64	-20.69	-27.33	-31.37	-36.15	-36.15	-36.15	-36.15	-36.15	-36.15	-36.15	-36.15
MG	**Total**	-3.24	-9.59	-17.20	-22.19	-24.40	-27.20	-25.22	-23.23	-21.25	-19.26	-17.27	-15.29	-13.30
	Sugarcane production	1.08	2.25	3.70	5.22	6.82	8.43	10.04	11.65	13.26	14.87	16.48	18.09	19.70
	Δ Soil C stock and N_2O emissions	0.01	0.04	0.09	0.17	0.25	0.34	0.44	0.53	0.62	0.71	0.81	0.90	0.99
	Δ Biomass C stock	-4.41	-11.58	-18.20	-20.70	-21.81	-23.00	-23.00	-23.00	-23.00	-23.00	-23.00	-23.00	-23.00
PR	**Total**	-3.32	-9.29	-14.42	-15.32	-14.74	-14.22	-12.52	-10.82	-9.11	-7.41	-5.71	-4.01	-2.31
	Sugarcane production	8.58	18.68	30.02	41.77	54.35	66.99	79.63	92.27	104.91	117.55	130.19	142.83	155.46
	Δ Soil C stock and N_2O emissions	0.06	0.07	0.13	0.30	0.54	0.83	1.13	1.42	1.72	2.02	2.31	2.61	2.90
	Δ Biomass C stock	-18.91	-59.29	-101.51	-122.64	-131.40	-140.71	-140.71	-140.71	-140.71	-140.71	-140.71	-140.71	-140.71
SP	**Total**	-10.28	-40.54	-71.36	-80.57	-76.51	-72.88	-59.95	-47.02	-34.08	-21.15	-8.21	4.72	17.65
	Sugarcane production	12.10	26.49	43.19	61.12	80.61	100.66	120.71	140.76	160.81	180.85	200.90	220.95	241.00
	Δ Soil C stock and N_2O emissions	0.07	0.05	0.06	0.31	0.68	1.18	1.68	2.19	2.69	3.19	3.69	4.20	4.70
	Δ Biomass C stock	-33.61	-98.40	-172.97	-221.72	-247.47	-274.50	-274.50	-274.50	-274.50	-274.50	-274.50	-274.50	-274.50
South Central	**Total**	-21.45	-71.86	-129.71	-160.30	-166.18	-172.66	-152.11	-131.56	-111.01	-90.46	-69.90	-49.35	-28.80

APPENDIX F (continued) – Accumulated GHG balance (in Tg CO_2eq) by the year 2030, due to dLUC and sugarcane cultivation during the years of 2006 to 2011 in south-central Brazil.

States	Evaluated criteria	Accumulated GHG balance (in Tg CO_2eq)											
		2019	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
	Sugarcane production	21.47	23.24	25.02	26.79	28.57	30.34	32.11	33.89	35.66	37.44	39.21	40.98
	Δ Soil C stock and N_2O emissions	-1.48	-1.60	-1.72	-1.84	-1.96	-2.08	-2.20	-2.30	-2.38	-2.37	-2.38	-2.38
	Δ Biomass C stock	-36.50	-36.50	-36.50	-36.50	-36.50	-36.50	-36.50	-36.50	-36.50	-36.50	-36.50	-36.50
GO	**Total**	-16.51	-14.86	-13.20	-11.55	-9.89	-8.24	-6.58	-4.91	-3.21	-1.43	0.33	2.11
	Sugarcane production	8.81	9.47	10.12	10.77	11.42	12.08	12.73	13.38	14.04	14.69	15.34	15.99
	Δ Soil C stock and N_2O emissions	0.88	0.95	1.02	1.10	1.17	1.24	1.32	1.38	1.41	1.44	1.46	1.47
	Δ Biomass C stock	-8.46	-8.46	-8.46	-8.46	-8.46	-8.46	-8.46	-8.46	-8.46	-8.46	-8.46	-8.46
MT	**Total**	1.23	1.96	2.68	3.41	4.13	4.86	5.59	6.30	6.99	7.67	8.34	9.00
	Sugarcane production	16.43	17.83	19.22	20.61	22.00	23.39	24.79	26.18	27.57	28.96	30.35	31.75
	Δ Soil C stock and N_2O emissions	1.61	1.77	1.93	2.08	2.24	2.40	2.55	2.70	2.86	2.99	3.09	3.13
	Δ Biomass C stock	-29.68	-29.68	-29.68	-29.68	-29.68	-29.68	-29.68	-29.68	-29.68	-29.68	-29.68	-29.68
MS	**Total**	-11.63	-10.08	-8.54	-6.99	-5.44	-3.89	-2.34	-0.80	0.75	2.28	3.77	5.20
	Sugarcane production	24.92	26.90	28.88	30.87	32.85	34.83	36.81	38.79	40.78	42.76	44.74	46.72
	Δ Soil C stock and N_2O emissions	-0.09	-0.08	-0.08	-0.07	-0.07	-0.07	-0.06	-0.05	-0.01	0.05	0.06	0.07
	Δ Biomass C stock	-36.15	-36.15	-36.15	-36.15	-36.15	-36.15	-36.15	-36.15	-36.15	-36.15	-36.15	-36.15
MG	**Total**	-11.32	-9.33	-7.35	-5.36	-3.38	-1.39	0.60	2.59	4.62	6.66	8.65	10.64
	Sugarcane production	21.31	22.92	24.53	26.14	27.75	29.35	30.96	32.57	34.18	35.79	37.40	39.01
	Δ Soil C stock and N_2O emissions	1.08	1.18	1.27	1.36	1.45	1.55	1.64	1.72	1.79	1.83	1.84	1.85
	Δ Biomass C stock	-23.00	-23.00	-23.00	-23.00	-23.00	-23.00	-23.00	-23.00	-23.00	-23.00	-23.00	-23.00
PR	**Total**	-0.60	1.10	2.80	4.50	6.20	7.91	9.61	11.30	12.98	14.62	16.25	17.87
	Sugarcane production	168.10	180.74	193.38	206.02	218.66	231.30	243.94	256.58	269.22	281.85	294.49	307.13
	Δ Soil C stock and N_2O emissions	3.20	3.49	3.79	4.08	4.38	4.67	4.97	5.20	5.49	5.72	5.84	5.90
	Δ Biomass C stock	-140.71	-140.71	-140.71	-140.71	-140.71	-140.71	-140.71	-140.71	-140.71	-140.71	-140.71	-140.71
SP	**Total**	30.59	43.52	56.46	69.39	82.33	95.26	108.19	121.07	134.00	146.86	159.63	172.33
	Sugarcane production	261.05	281.10	301.15	321.20	341.25	361.30	381.34	401.39	421.44	441.49	461.54	481.59
	Δ Soil C stock and N_2O emissions	5.20	5.70	6.21	6.71	7.21	7.71	8.22	8.65	9.17	9.67	9.92	10.05
	Δ Biomass C stock	-274.50	-274.50	-274.50	-274.50	-274.50	-274.50	-274.50	-274.50	-274.50	-274.50	-274.50	-274.50
South Central	**Total**	-8.25	12.30	32.85	53.40	73.96	94.51	115.06	135.54	156.11	176.65	196.96	217.14