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

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2016

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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

To my grandmother Ofélia, my brother Marcelo, and my girlfriend Vanessa, for all we went through together with much love, care and dedication.

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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.

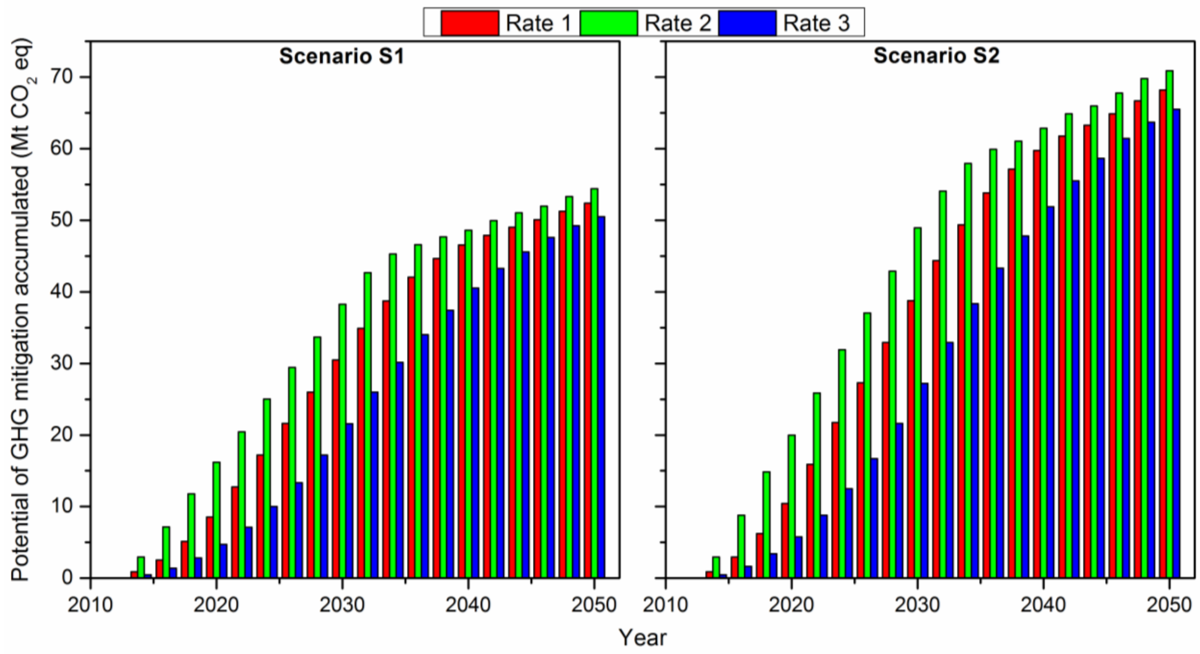

Figure 1. Avoided greenhouse gas emissions (in Mton CO_2equivalent) from 2012 to 2050 due to the conversion of remaining sugarcane areas harvested with burning (2011 harvest season – 1,670,521 ha) to green harvest scenarios in São Paulo State – Brazil, S1 (conventional soil tillage) or S2 (reduced soil 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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