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SOIL CARBON BALANCE IN LONG-TERM NO-TILL IN A SUB-TROPICAL ENVIRONMENT

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SOIL CARBON BALANCE IN LONG-TERM NO-TILL IN A SUB-TROPICAL ENVIRONMENT

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To all of those who dedicate their lives to human progress,

I offer.

To my Family for being my first and eternal teachers,

I dedicate.

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Xanthippe – Socrates, it’s the end, they condemned you.
Socrates – They are also condemned by nature.
Xanthippe – But the sentence was unfair.
Socrates – And you would like it to be fair?
(Socrates 399 b.c.)

PRESENTATION

This thesis was written according to "Manual de normatização bibliográfica para trabalhos científicos, UEPG (2012)" and is composed of the following chapters:

- Soil type and texture impacts on soil organic carbon storage in a sub-tropical agro-ecosystem, published in Geoderma journal, Geoderma 286 (2017) 88–97.
- Soil carbon inventory to quantify the impact of land use change to mitigate greenhouse gas emission and ecosystem services, under review in Environmental pollution journal.
- Conservation agriculture based on diversified and high-performance production system leads to soil carbon sequestration in sub-tropical environments, under review in Geoderma journal.

All the chapters reproduce literally the text submitted to the journals and despite interconnections one chapter is independent of the others (the read of any chapter don't presume the read of the others and the acronyms, equations, figures, tables and references refers only to the current chapter). Preceding the first chapter there is a general introduction and the last item is composed by the general conclusions.

SOIL CARBON BALANCE IN LONG-TERM NO-TILL IN A SUB-TROPICAL ENVIRONMENT

ABSTRACT

Soils can be a source or sink of atmospheric CO_2, according to land use and management. Currently the land use and land use change (LULUC) emits 1.3 ± 0.5 Pg carbon (C) year^{-1}, equivalent to 8% of the global annual emission. Techniques such as low carbon agriculture, has been developed to sequester C in soils and reduce greenhouse gas (GHG) emissions. However, besides political and social challenges for the system adoption, there’s still great uncertainty related to its real mitigation potential. This study aimed: i) Quantify the historical and current main sources of GHG emissions for Campos Gerais region in Paraná state, Brazil; ii) quantify the potential of long term (30 years) agricultural best management practices, based on the three pillars of conservative agriculture: permanent soil cover, crop rotation and no-till, to sequester C in soils, using Paiquerê farm (located in Campos Gerais region) as a successful model; iii) estimate the impact of best management practices adoption in the region croplands and globally for the next 100 years where is suitable using Century and Roth-C models. The GHG emission sources were presented as an inventory and showed that historical (1930 – 2017) GHG emissions in the region was 412.18 Tg C, in which LULUC contributes 91% (376.2±130 Tg C). Forestry sequestered 51.7 ± 23.9 Tg C in 0.6 Mha in 47 years (1.8 Tg C Mha^{-1} year^{-1}) and no-till sequestered 30.4 ± 23.9 Tg C in 1.9 Mha in 32 years (0.5 Tg C Mha^{-1} year^{-1}). Both models performed well, and Century was more efficient for simulate the SOC stocks, the mean residue was 10 Mg C ha^{-1} (13%) for n = 91. The model residue increased along with the oxides content in the soil clay fraction, suggesting that mineralogical control inclusion can reduce the model simulation bias. Century predictions showed that the system currently practiced at Paiquerê farm have the potential to mitigate 13 years of regional total emissions (330 Tg C in 100 years) or 105 years of agriculture, forestry and other land use (AFOLU) sector emissions (40 Tg in 100 years) in the region. In the same way, it has the potential to sequester 2.5±0.02 Pg C at 0-20 cm and 11.7±3 Pg C at 0-100 cm soil depth in 86 million ha globally. This is equivalent to 11% of global annual emissions from LULUC sector. In this way, our methodology can be used as a model to access the potential of conservation agriculture to sequester C and support public policies aiming to mitigate GHG emissions.

Key words: conservative agriculture, Century models, Roth-C model, IPCC tier 2, geographic information system.

BALANÇO DE CARBONO DO SOLO EM PLANTIO DIRETO DE LONGA DURAÇÃO EM UM AMBIENTE SUB-TROPICAL

RESUMO

Solos podem ser uma fonte ou um dreno de CO_2 atmosférico, dependendo do seu sistema de manejo. Atualmente, o uso do solo e mudança de uso do solo emitem 1,3 ± 0,5 Pg C ano^{-1}, equivalente a 8% das emissões globais. Técnicas como a agricultura de baixa emissão de C têm sido desenvolvidas para sequestrar C nos solos e reduzir a emissão de gases do efeito estufa. Porém, além dos desafios políticos e sociais envolvendo a doção destes sistemas, ainda há muita incerteza sobre o seu real potencial de mitigação. Assim, os objetivos desse estudo foram: i) Quantificar as fontes históricas e atuais de emissão de gases do efeito estufa na região dos Campos Gerais do Paraná, Brasil; ii) quantificar o potencial das melhores práticas de manejo agrícola baseadas nos três pilares da agricultura de conservação: Solo permanentemente coberto, plantio direto e rotação de culturas, em longo prazo (30 anos) para sequestrar carbono no solo, utilizando a fazenda Paiquerê (localizada na região dos Campos Gerais) como um modelo de sucesso; iii) estimar o impacto da adoção das melhores práticas de manejo nas áreas agrícolas da região e globalmente onde adequadas pelos próximos 100 anos utilizando os modelos Century e Roth-C. As fontes de gases do efeito estufa foram apresentadas como um inventário e mostraram que as emissões históricas (1930 – 2017) foram 412,18 Tg C, no qual as mudanças de uso do solo contribuíram com 91% (376,2±130 Tg C). As florestas sequestraram 51.7 ± 23.9 Tg C em 0.6 Mha em 47 anos (1.8 Tg C Mha^{-1} ano^{-1}) e o plantio direto sequestrou 30.4 ± 23.9 Tg C em 1.9 Mha em 32 anos (0.5 Tg C Mha^{-1} ano^{-1}). Ambos os modelos tiveram uma boa performance e o modelo Century foi mais eficiente em simular os estoques de carbono do solo, o resíduo médio da simulação foi 10 Mg C ha^{-1} (13%) para n = 91. O resíduo do modelo aumentou com a quantidade de óxidos no solo, sugerindo que a inclusão do controle mineralógico pode reduzir o viés de simulação. As predições do Century mostraram que o sistema tem potencial para mitigar 13 anos de emissões regionais (330 Tg C em 100 anos) ou 105 anos de emissões do setor agricultura, floresta e pecuária (40 Tg em 100 anos) na região. Da mesma forma, globalmente o sistema apresenta um potencial para sequestrar 2,5 ± 0.02 Pg C na profundidade 0–20 cm e 11,7 ± 3 Pg C na profundidade 0-100 cm em 86 milhões de ha distribuídos por todo o mundo. Este valor é equivalente à 11% das emissões globais dos setores agricultura, floresta e pecuária e mudanças de uso do solo. Assim, a nossa metodologia possa ser utilizada como um modelo para divulgar o potencial da agricultura conservacionista em sequestrar C nos solos e suportar políticas públicas que visem à mitigação das emissões de gases do efeito estufa.

Palavras-chave: agricultura conservacionista, modelo Century, modelo Roth-C, tier 2 IPCC, sistemas de informação geográfica.

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ACRONYMS AND TERMS LIST

AFOLU – Agriculture, forestry and other land use change

C – Carbon

EU – European Union

GHG – Greenhouse gases

GIS – Geographic information systems

IPCC – International panel on climate change

LULUC – Land use and land use change

SOC – Soil organic carbon

UK – United Kingdom

No-till – Crop system in which the seeding operation is performed without soil plough, cutting the straw above soil with drillers

Conservation agriculture (conservative practices) – Crop system based on the three pillar of conservation agriculture (Permanent soil cover, no-till and crop rotation)

Best management practices (conservative best management practices) – Crop system based on the three pillars of conservation agriculture allied with the use of terraces to control soil erosion, high fertilization rates, high crop yields and intense crop rotation (four or more crops in two years)

SUMMARY

GENERAL INTRODUCTION

The historical emissions by LULUC since the beginning of industrial era accounts for 227 ± 74.5 Pg C, 78 Pg C of which has been emitted through soil cultivation and 67 Pg C has been emitted through burning of natural vegetation (HOUGHTON, 2014, LAL, 2004, LE QUÉRÉ et al., 2015). As the second biggest C pool on Earth, 2500 Pg of which 1550 is soil organic C (SOC), soils can act as a sink of C, reducing atmospheric CO_2 concentration depending on land use and management (LAL, 2004). In this way, technologies such as conservation agriculture (LADHA et al., 2016, SÁ et al., 2017) have been developed to reduce GHG emissions from land cultivation and sequester C in soils. Lal (2004) reported that 0.4 to 0.8 Pg C yr^{-1} could be sequestered in the world croplands (1350 Mha) with the adoption of conservation agriculture practices. Recently, Sá et al. (2017) reported that the adoption of conservation agriculture in South America could mitigate 0.28 Pg C yr^{-1} for 35 years. These proposals fit well in the SOC four per mille plan, discussed in the COP 21 United Nation sustainable innovation forum. This plan aims to increase the world soil C stocks by 0.04% per year for next 20 years (MINASNY et al. 2017).

Several studies explored C dynamics in conservative agricultural systems and supported these management options (DIEKOW et al., 2005, MISHRA et al., 2010, NADEU et al., 2015, SÁ et al., 2014). However, due to some knowledge gaps: i) relative absence of long term field experiments (with more than 30 years) (RASMUSEN et al., 1998); ii) Relative absence of production farming system under long-term conservative practices; iii) Lack of observational data, there’s still great uncertainties about the potential of conservation agriculture to sequester C in soils and mitigate GHG emissions (POWLSON et al., 2014). Some studies even reported that the system potential to sequester C in soils could be too low for meaningful mitigation (POWLSON et al., 2014, VANDENBYGAART, 2016).

As a tool to organize the available information and develop strategies for the adoption and maintenance of mitigations technologies, GHG inventories are being developed in many countries. Su et al. (2016) using IPCC methodology performed a GHG emission inventory for all EU countries. They report Germany, UK and France as the higher, and Cyprus, Malta and Latvia and the lower GHG emitters. In the same way, Diana et al. (2017) mapped the C footprint of EU regions. They reported UK having the highest and Bulgaria and Romania with the lowest C footprint. The variable that most explained higher C footprints was income. These inventories play a fundamental role in providing a basis for the development of public policies. However, it is rarely being conducted for developing countries (e.g. Southeast Asian, African, and South American).

The same way, as a tool for explore large spatial and temporal scales in the absence of long term experiments, ecosystems models have been widely used to study factors that drive SOC storage. The ecosystem models can be classified in: i) Empirical models that describe the observed behavior without describe the process; ii) Conceptual models that describe the relationship between the variables in a conceptual way; iii) Physically based models, also known as process based models, that describe the physical process involved in the variables relationships (usually with mathematical equations) and look for predictions consistent with observations (WAINWRIGHT and MULLIGAN, 2004). Another classification includes: i) Conceptual/understanding models that are used to understand the structure and functioning of an ecosystem; ii) strategic decision models that are used to address policy goals, usually in long term; and iii) tactical decision models that are used to address tactical operations usually in short term (FAO, 2008). Currently, there is a tendency of lump models from different fields (hydrology, biogeochemistry, etc.) in Earth system models for understand global cycles and answer the current knowledge gaps (LUO et al. 2015; WIEDER et al. 2015). In Brazil, process based SOC models has been used to study SOC dynamics in Amazon Basin (CERRI et al., 2007; SILVER et al., 2000), sugar cane plantations and forested areas (GALDOS et al., 2009; LIMA et al., 2011), and crop system of south region (TORNQUIST et al. 2009). However, although extensively validated in temperate agroecosystems (CONG et al., 2014; KELLY et al., 1997; SMITH et al., 1997) its application is still incipient in tropical and sub-tropical ecosystems.

Thus, the objectives of this study were: i) Quantify the historical and current main sources of GHG emissions for Campos Gerais region in Paraná state, Brazil; ii) Quantify the potential of long term (30 years) agricultural best management practices, based on the three pillars of conservative agriculture: permanent soil cover, crop rotation and no-till, to sequester C in soils, using Paiquerê farm (located in Campos Gerais region) as a successful model; iii) Estimate the impact of best management practices adoption in the whole region and globally for the next 100 years where is suitable using Century and Roth-C models. In this way, our methodology can be used as a model to access the potential of conservation agriculture to sequester C and support public policies aiming to mitigate GHG emissions.

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CHAPTER 1 - SOIL TYPE AND TEXTURE IMPACTS ON SOIL ORGANIC CARBON STORAGE IN A SUB-TROPICAL AGRO-ECOSYSTEM

Abstract: Soil organic carbon (C) plays a fundamental role in tropical and sub-tropical soil fertility, agronomic productivity, and soil health. As a tool for understand ecosystems dynamics, mathematical models such as Century have been used to assess soil's capacity to store C in different environments. However, as Century was initially developed for temperate ecosystems, several authors have hypothesized that C storage may be underestimated by Century in Oxisols. We tested the hypothesis that Century model can be parameterized for sub-tropical soils and used to reliably estimate soil organic carbon (SOC) storage. The aim of this study was to investigate SOC storage under two soil types and three textural classes and quantify the sources and magnitude of uncertainty using the Century model. The simulation for SOC storage was efficient and the mean residue was 10 Mg C ha^{-1} (13%) for n = 91. However, a different simulation bias was observed for soil with < 600 g kg^{-1} of clay, 16.3 Mg C ha^{-1} (18%) for n=30, and at > 600 g kg^{-1} of clay, was 4 Mg C ha^{-1} (5%) for n=50, respectively. The results suggest a non-linear effect of clay and silt contents on C storage in Oxisols. All types of soil contain nearly 70% of Fe and Al oxides in the clay fraction and a regression analysis showed an increase in model bias with increase in oxides content. Consequently, inclusion of mineralogical control of SOC stabilization by Fe and Al (hydro) oxides may improve results of Century model simulations in soils with high oxides contents.

Key Words: Long term no-till, Oxisols, Oxides, Modelling, Century model.

List of acronyms: CD, Coefficient of determination; CS, Crop sequence; EF, Modeling efficiency; InAn, Inceptisol Anthrept; InDy, Inceptisol Dystrudept; M, Average residue, RE, Relative error; RH, Rhodic Hapludox; RMSE, Root mean square error; SOC, Soil organic carbon; SOM, Soil organic matter; SSA, Specific surface area; TH, Typic Hapludox; TN, Total nitrogen.

1.2 INTRODUCTION

Soil organic carbon (SOC) storage at a location is controlled by various environmental factors including climate, vegetation, relief, parent material, soil texture, and land use (JENNY, 1994; STEVENSON, 1999). Highly weathered soils are characterized by low pH, high exchangeable Al, low base saturation and phosphorus content (CAIRES et al., 2006; FOX, 1980; SÁ et al., 2009). Overall, increasing C storage of these soils has been reported as the key to improve soil fertility, restoring soil resilience, enhancing soil quality, and sustaining agronomic productivity (BURLE et al., 1997; LAL, 2015; SÁ and LAL, 2009; SÁ et al., 2014).

Ecosystem models have been used to study factors that drive C storage in soils and generate scenarios to study SOC dynamics at large spatial and temporal scales. Although several models have been applied in agro-ecosystems to assess SOC storage, Century is one of the most adapted model for diverse agro-ecosystems (PARTON et al., 1987; PARTON et al., 1988). The model was initially developed to simulate the C and nitrogen (N) dynamics of North American prairies soils in temperate zones (PARTON et al., 1987; PARTON et al., 1988). Century has been applied to study different soil management impacts such as fertilizer application (CONG et al., 2014), the effect of fire (RICHARDS et al., 2011), soil plowing (ÁLVARO-FUENTES et al., 2009), organic manure application (SMITH et al., 1997), irrigation (LIU et al., 2011), and grazing (KELLY et al., 1997) on SOC across a variety of agro-ecosystems.

Century model simulations have been widely validated in temperate agro-ecosystems (CONG et al., 2014; KELLY et al., 1997; SMITH et al., 1997). The authors reported that the Century model successfully predicted C and N dynamics in various conditions but needed improvement to predict C dynamics in specific situations such as forested systems. In tropical ecosystems, Century has been used to study the SOC dynamics in Amazon Basin (CERRI et al., 2007; SILVER et al., 2000), authors reported that Century was able to simulate SOC dynamics when information such as crop productivity was available, however the model underestimated SOC storage specially in sandy clay soils. Under sugar cane plantations, and forested areas (GALDOS et al., 2009a; GALDOS et al., 2009b; LIMA et al., 2011), authors reported higher bias in simulation results in soils with lower C contents. In southern Brazil, Tornquist et al. (2009a) reported a reasonable estimation of SOC storage under no-till (NT) cropping systems. They attributed inconsistencies between observed and simulated values to model treatment of clay mineralogy.

Several studies have demonstrated that the mineralogy of clay and silt fraction plays an important role in C stabilization (BRUUN et al., 2010; KAISER and GUGGENBERGER, 2003; SAIDY et al., 2013; TORN et al., 1997). The association of clay and silt particles with soil C, build-up clay-humic complexes that play a fundamental role in C protection against microbial oxidation (SIX et al., 2002). Some authors reported that the inclusion of soil types (BRUUN et al., 2010) and clay mineralogy (i.e. Fe and Al (hydro) oxides) (BRUUN et al., 2010; LEITE and MENDONÇA, 2003) can reduce the simulation bias of ecosystem models.

To simulate the soil texture effect on C storage, the Century model assumes that the decomposition of soil organic matter (SOM) by microbial biomass and the stabilization of SOC in soils have a linear relationship with clay and silt contents, and the mineralogy of the clay and silt fractions does not affect SOC stabilization. These assumptions have been made based on studies conducted in soils with 2:1 (i. e. isomorphic substitution permanent negative charges) clay mineralogy in the USA (LEITE and MENDONÇA, 2003). For simplification, the soil minerals effect on SOC stabilization is considered as a function of the mineral specific surface area (SSA).

We hypothesized that a reliable estimate of SOC storage can be made by parameterizing the Century model for sub-tropical soils. Additionally, we assumed a non-linear relationship of silt + clay minerals on soil C stabilization. Thus, the aims of this study were to: i) Calibrate the Century model to study the impact of soil types and clay mineralogy on SOC storage in an on-site farm managed for 30 years under no-till; ii) validate the results with measured SOC stocks; iii) quantify the magnitude and sources of uncertainties; and iv) test whether Century equations that consider the effect of silt + clay content on SOC storage (largely parameterized for temperate ecosystems) are able to simulate C storage in tropical and sub-tropical soils with high content of Fe and Al (hydro) oxides.

1.3 MATERIAL AND METHODS

1.3.1 Study area

This study was conducted at Paiquerê Farm, located at Piraí do Sul city, State of Paraná, Southern Brazil (24°S 20’ 20” and 50° W 07’ 31”, Figure 1.1). This site was chosen because the entire farm adopted no-till over 30 years, with high crop yields and high C input to soil through crop residues decomposition. The farm is managed in 24 plots divided in 3 crop sequences and each crop sequence comprises 33% of the farm’s land area. In the winter, 2 crop sequences occupying - 66% of the area, were being cultivated with wheat (*Triticum* *aestivium* L.) and another crop sequence occupying 33%, with black oat (*Avena sativa* L.). In the summer, soybean (*Glycine max* L.) is cultivated after wheat and maize (*Zea mays* L.) after black oat. The crop sequence (CS) is comprised by Wheat/Soybean, hereafter is designated as CS1 and occupy 33% of the farm surface area; Wheat/Soybean for the second consecutive year (occupying 33%) is designated as CS2, and Oat/Maize, is designated as CS3 which also represents 33% of the farm surface area. At each year the CS is rotating from CS1 to CS2, CS2 to CS3 and CS3 to CS1.

The relief of the farm has slightly undulated landscape with slopes ranging from 3 to 10%. The soil types identified in the farm are: 1) Latossolo Vermelho, Brazillian Classification (EMBRAPA, 2010) and equivalent to Rodhic Hapludox in USDA, Soil Taxonomy classification (SOIL SURVEY, 2014); 2) Latossolo Vermelho Amarelo, Brazillian Classification (EMBRAPA, 2010) and equivalent to Typic Hapludox (Soil Taxonomy, SOIL SURVEY, 2014); equivalent to; 3) Cambissolo Húmico, Brazillian Classification (EMBRAPA, 2010) and equivalent to Inceptisol Anthrept (Soil Taxonomy, SOIL SURVEY, 2014). This soil originally had humic characteristics, but after cultivation, the SOM was stabilized at lower contents; and 4) Cambissolo Háplico, Brazillian Classification (EMBRAPA, 2010) and equivalent to Inceptisol Dystrudept (Soil Taxonomy, SOIL SURVEY, 2014)(Figure 1.1).

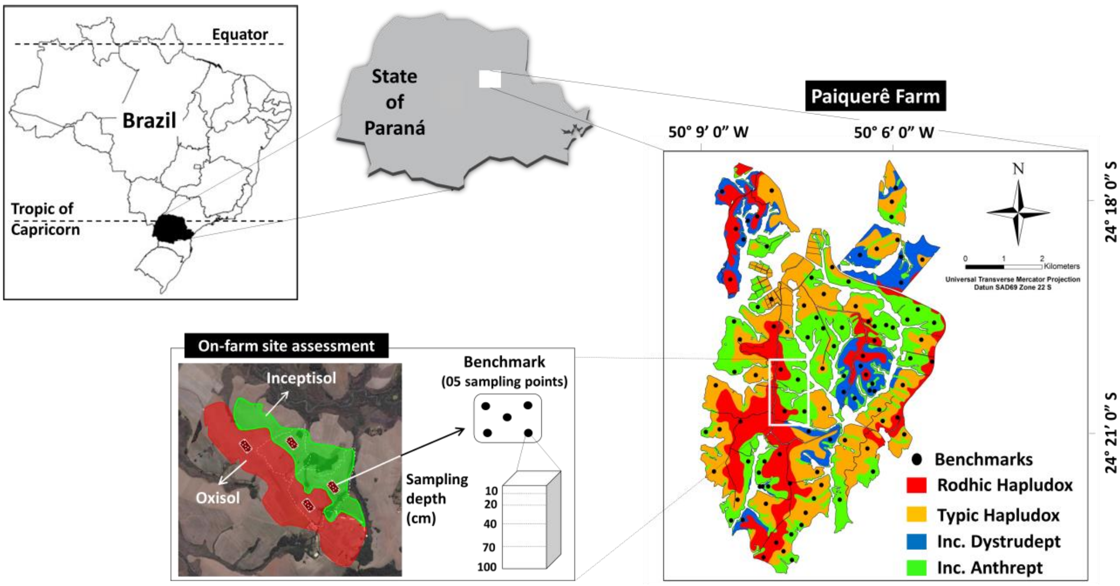

Figure 1: Localization of the study area - Paiquerê Farm, benchmarks locals and representative scheme of a benchmark.
*The soil map and altitude quotes were obtained from the farm database.

The mean altitude of the area is 970 m above sea level and the climate is classified as Cfb by Köeppen classification, characterizing a sub-tropical humid climate (MAACK, 1981). The annual temperatures ranged between 25.9 °C, and 13.5 °C (IAPAR, 2013; http://www.iapar.br/modules/conteudo/conteudo.php?conteudo=1070), and the mean precipitation is 1717 mm (Table 1.1). The parent material of the study area is comprised mainly of shales from the Ponta Grossa formation (MINEROPAR, 2013; http://www.mineropar.pr.gov.br/modules/conteudo/conteudo.php?conteudo=154). The natural vegetation of the farm was composed by fields of C_4 species such as *Andropogon sp., Aristida sp., Paspalum sp., and Panicum sp.* (BEHLING, 1997).

Table 1.1: Historical 27 years (1986 - 2013) monthly mean precipitation and temperature in Paiquerê farm.

Months	Preciptation (mm)			Mean temperature (°C)		
	Minimum	Maximum	Mean	Minimum	Maximum	Mean
January	98	550	264	18	28.9	22.5
February	62	316	176	18	29.1	22.4
March	28	250	125	16.7	28.5	21.4
April	12	255	99	14.2	26.3	19.1
May	7	363	137	10.6	22.9	15.5
June	2	333	124	9	21.7	14
July	5	260	91	8.3	21.9	13.8
August	0	257	70	9.1	24.1	15.3
September	17	329	146	11.5	24.8	17.1
October	24	308	148	14.2	26.8	19.6
November	3	299	138	15.6	27.9	20.9
December	57	356	208	17.2	28.6	22.1
Average	26.5	323	143.8	13.5	25.9	18.6

*The data were obtained from the meteorological stations of the farm and IAPAR.

1.3.2 Soil sampling

Bulk soil samples were collected from 30 x 30 m pre-defined areas denominated by benchmarks in each soil type on the landscape (Figure 1.1). The samples were collected at depths of 0-10, 10-20, 20-40, 40-70, and 70-100 cm, mixing five sub-samples in each depth per benchmark using an auger (GONÇALVES et al., 2015). For this study the results of two depths 0-10 and 10-20 cm were used to run the Century model to simulate C storage for the 0-20 cm soil layer that was the depth in which SOC storage is simulated by Century v 4.0.

The criteria used to define the 91 benchmarks places (Figure 1.1) was based on soil type and textural class. The most predominant soil types on farm's surface (e.g. Rodhic Hapludox represents about 15% and Typic Hapludox represents about 30% of farm's surface) received more benchmarks, and the textural class was assessed distributing the benchmarks according to landscape position, using it as a proxy, as the summit tends to be more clay than the shoulder and the foot toe in soil catena (SÁ et al. 2013). This strategy was developed aiming to group benchmarks with the same soil type and textural class, thus the influence of both variables in the model bias can be tested.

Undisturbed soil samples were collected in pits (70 × 70 cm) with 5 x 5 cm volumetric rings in all the 5 depths to calculate soil bulk density (ρ_b) by the core method (BLAKE and HARTGE, 1986). Two core samples were obtained from middle of each depth increment per pit, and then were oven-dried at 105 ºC for 48 to 72 h, and ρ_b was computed as weight:volume ratio and expressed as Mg m^{-3}.

1.3.3 Sample preparation and analysis

1.3.3.1 Chemical and particle size determinations

The samples of the first two depths (0-10 and 10-20 cm) were prepared and analyzed at the Soil Organic Matter Laboratory of Ponta Grossa State University. Briefly, the samples were dried in an oven at 40 °C until constant weight, then ground with a wood roll and passed through a 2 mm sieve. Soil pH was determined in a 0.01 mol L^{-1} $CaCl_2$ suspension (1:2.5 v/v soil/solution). Exchangeable Ca^{2+}, Mg^{2+} and Al^{3+} were extracted with 1 mol L^{-1} KCl solution and P and K^+ with Melich-1 solution. Exchangeable Al^{3+} was determined by titration with 0.025 mol L^{-1} NaOH, Ca^{2+} and Mg^{2+} were determined by titration with 0.025 mol L^{-1} EDTA, P by colorimetry and K^+ by flame photometry. Soil texture was determined by the densimeter method using a Bouyoucous scale (GEE et al., 1986).

1.3.3.2 Separation of clay fraction for X-Ray pattern determination

An aliquot of 40 g of oven dried and sieved soil was weighed, and the organic matter was removed by hydrogen peroxide 30%. After that, the aliquot was placed in a plastic pot and was added 100 ml of deionized water. The pot was placed in a freezer at 2 C° for 16 hours and then shaken at 100 rpm in a horizontal shaker for four hours. After, the soil was washed in a 53 µm sieve to separate the sand fraction, the silt was separated of the clay fraction trough sedimentation according to Stokes law (JACKSON, 1979). The clay fraction was washed with alcohol and water 1:1 and then dried at 40 °C and the type of the clay fractions was obtained by x-ray diffraction (RIGAKU Ultima IV). The relative amount of the clay minerals was obtained by a semi-quantitative method described in Moore and Reynolds Jr. (1997), using Taylor series to calculate the area formed by the peaks and the baseline in all the soil types X-Ray patterns (Figure 1.2) for calculations of the percentage of oxides the software R v. 3.2.2.was used.

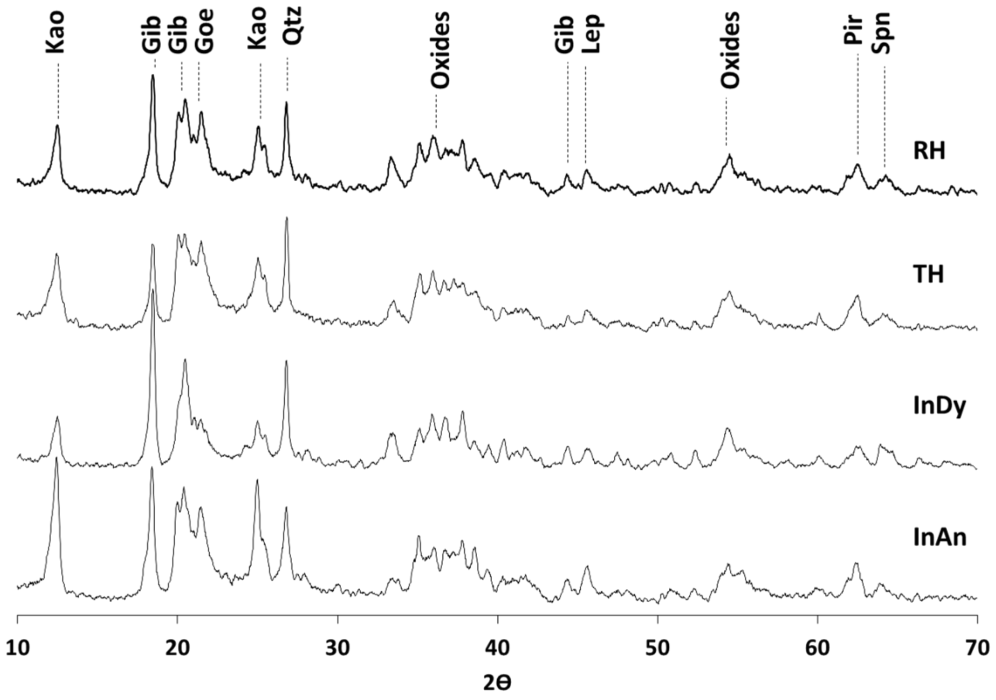

Figure 2: Clay fraction XRD patterns of all soil types.

*Kao = Kaolinite; Gib = Gibbsite; Goe = Goethite; Lep = Lepidocrocite; Pir = Pyrite; Spn = Spinel; Qtz = Quartz; Oxides = Group of mixed oxides, usually iron oxides.
* RH = Rhodic Hapludox; TH = Typic Hapludox; InAn = Inceptisol Anthrept; InDy = Inceptisol Dystrudept.

1.3.4 Carbon and nitrogen concentration and stock calculations

Total C and N were determined by dry combustion at 950° C in an elemental CN analyzer (Truspec CN LECO® 2006, St.Joseph, EUA) and was designated soil organic carbon (SOC) because the total amount of inorganic C in soils of this region is smaller than 0.1% for Oxisols and 0.25% for Inceptisols, and other soil types are not derived from calcareous minerals (SÁ et al., 2013).

The mass of SOC on an area basis (Mg ha^{-1}) was computed according to Eq. (1), by multiplying the SOC (Kg of C per Kg of soil) by the bulk density (Mg m^{-3}), depth of soil sampling (m), and soil area (10,000 m^{2} ha^{-1}).

$$\text{SOC (Mg ha}^{-1}\text{)} = \text{Bd (Mg m}^{-3}\text{)} * \text{d (m)} * \text{SOC (Kg Kg}^{-1}\text{)} * \text{SA (m}^{2}\text{ ha} - 1\text{)} \qquad (1)$$

To assess the effect of soil types and texture on SOC storage, the benchmarks were grouped in scenarios, its characteristics are described in the table 1.2. The scenarios were created by grouping all the benchmarks with the same soil type and textural class. The soil texture was separated by clay content: < 350 (sandy clay); 350 to 600 (clay), and > 600 g clay kg^{-1} of soil (heavy clay). The bulk density for all the benchmarks in the same soil type was calculated by weighted average of all samples collected.

1.3.5 Effect of clay and silt content on SOC storage in Century model

Century comprises two plant C compartments, structural and metabolic, and three soil C compartments, active, slow and passive pools. Soil texture affects the decomposition of plant's material and C dynamics between compartments as described below:

1.3.5.1 Effect of texture on decomposition of active compartment

$$dCi/dt = Ki * A * \mathbf{Tm} * Ci \qquad (2)$$

Where: Ki is the maximum rate of decomposition of the compartment; A is the combined effect of temperature and moisture; Ci is the C content in the compartment, Tm is:

$$\mathbf{Tm =} (1 - 0.75\mathbf{T}) \qquad (3)$$

$$\mathbf{T = Silt + Clay} \qquad (4)$$

1.3.5.2 Effect of texture on the C fluxes from the active compartment

$$F_T = 0.17 - 0.68\mathbf{T} \qquad (5)$$

Where F_T is the C fraction lost by microbial respiration.

$$C_{LIX} = (H_2O_{30} / 18)\ (0.01 + 0.04\ \mathbf{Ts}) \qquad (6)$$

Where C_{LIX} is the C fraction lost by leaching, H_2O_{30} is the fraction of water leached under 30 cm depth (cm $month^{-1}$) and Ts is the sand content of soil.

$$C_{AP} = 0.003 + 0.032\ \mathbf{T_C} \qquad (7)$$

Where C_{AP} is the C fraction allocated to the passive compartment and T_C is the clay content of soil.

$$C_{AL} = (1 - C_{AP} - C_{LIX} - F_T) \qquad (8)$$

Where C_{AL} is the C fraction allocated to the slow compartment.

Table 1.2: Soil characteristics of the scenarios framed according to soil type and textural class, 0-20 cm depth.

Texture/	Particle size				Bulk Density	Stock		pH	H+Al^{3+}	Ca^{+2}	Mg^{+2}	K^{+}	P	n[§]
Soil type[‡]	Clay	Silt	Clay + Silt	Sand		SOC	TN	CaCl$_2$						
	----------------g kg^{-1}---------------				Mg m^{-3}	-------Mg ha^{-1}------			---------------cmolc dm^{-3}---------------				mg dm^{-3}	
HC - RH	720	130	850	150	1.06 c	77.85 abc	4.80 a	5.07 ns	6.95 ns	6.43 ns	1.59 ns	0.44 ns	4.10 ns	12
HC - TH	700	170	870	130	1.16 b	86.33 a	5.30 a	4.85	7.92	6.12	1.53	0.44	5.63	15
C - TH	490	220	710	290	1.16 b	80.60 abc	4.51 a	5.23	6.53	7.43	1.83	0.54	7.69	6
HC - InAn	650	210	860	140	1.03 d	82.30 ab	5.14 a	4.80	8.62	6.57	1.50	0.43	6.08	18
C - InAn	460	180	640	360	1.03 d	66.72 c	4.75 a	4.79	8.17	6.04	1.55	0.42	7.30	12
SdC - InAn	250	220	470	530	1.03 d	48.08 d	2.33 b	4.80	7.53	4.84	1.18	0.42	10.93	5
HC - InDy	660	210	870	130	1.19 a	73.42 abc	4.55 a	4.80	7.31	5.91	1.24	0.37	5.67	5
C - InDy	480	220	700	300	1.19 a	69.63 bc	4.33 a	5.01	6.57	6.45	1.42	0.53	4.82	7

*The means followed by different letters in columns differ from each other by LSD test at 95% of confidence.
ns = non-significant difference was found.

[‡] Texture and soil type: HC – RH, Heavy clay Rhodic Hapludox; HC – TH, Heavy clay Typic Hapludox; C – TH, Clay Hapludox; HC – Ian, Heavy clay Inceptisol Anthrept; C – Ian, Clay Inceptisol Anthrept; SdC – Ian, Sandy clay Inceptisol Anthrept; HC – IDy, Heavy clay Inceptisol Dystrudept; C – IDy, Clay Inceptisol Dystrudept; [§] n = number of observations.

1.3.5.3 Effect of texture on the C fluxes from the slow compartment

$$C_{LP} = 0.003 - 0.009\ \mathbf{T_C} \tag{9}$$

Where C_{LP} is the C fraction allocated to the passive compartment.

$$C_{LA} = (1 - C_{LP} - 0.55) \tag{10}$$

Where C_{LA} is the C fraction allocated to the active compartment.

For simplification, the model assumes a linear decrease of SOC in the active compartment with increasing silt and clay content (Eq. (2) and Eq. (3)). The C fraction loss by microbial respiration from the active compartment decreases with increasing silt and clay content (Eq. (5)), and the C fraction lost by leaching from the active compartment increases with increase in sand content (Eq. (6)). The C fraction allocated in the passive compartment originating from active compartment increases with increasing clay content (Eq. (7)), and C fraction allocated in the passive compartment originated from the slow compartment decreases with increase of clay content (Eq. (9)).

1.3.6 Initialization and calibration of Century for this study

Century v. 4.0 (as obtained from the website:

https://www.nrel.colostate.edu/projects/century/) was initialized as follows:

(i) First, the file “site.100” was edited by adding the farm’s latitude and longitude, monthly mean precipitation, minimum and maximum temperature obtained from the farm’s meteorological station, these parameters were common for all the simulation performed for each benchmark;

(ii) The files “crop.100” of wheat, soybean and maize were edited and calibrated according indexes “Grain Yield/Shoot” and “Root/Shoot” obtained for the study region reported by Sá et al. (2014); and crop yields that were obtained from Paiquerê farm for the period of 1997 to 2013 (GONÇALVES et al., 2015). The crop yields were used to estimate C input from shoot and roots, these three variables were adjusted altering the Century parameters of potential aboveground monthly production “PRDX”, initial “FRCT(1)”, and final “FRCT(2)”, fraction of C allocated to the roots and maximum harvest index “HIMAX” for each crop file, to simulate the C added to soil by root, and shoot and the C extracted by harvest;

(iii) The values of grain yield, shoot and root C were validated by comparing the measured values with the output variables of economic yield of C in grain + tubers for grass/crop “cgrain”, C in aboveground live for grass/crop , “aglivc” and C in belowground live for grass/crop, “bglivc” (Table 1.3).

(iv) The files of black oat (*Avena sativa*) and rice (*Oryza sativa*), were calibrated like the others “crop.100” files based on the indices reported by Sá et al. (2014) and Fageria (2000), black oat grain yield was considered similar to wheat.

(v) The files, “cult.100”, “fert.100”, “fire.100”, “fix.100”, “graz.100” and “harv.100” used “default” values from Century and were adjusted to compose the “schedule” file for simulate the events that occurred in the farm between 1966 and 2013 (Table 1.4), the model was run and the calibration procedure started.

(vi) Files of native vegetation and pasture were calibrated altering the Century parameters of potential aboveground monthly production for crops “PRDX”, until the output variable “SOMTC”, that correspond to SOC stocks, match with the 2013 measured SOC stocks of a group of samples used for the model calibration, the mean texture of that group of samples was 700 g kg^{-1} of clay, 15 g kg^{-1} of silt and 15 g kg^{-1} of sand, it was chosen because most part of the farm soils (53 of 91 samples) contains more than 600 g kg^{-1} of clay (mean of 68%). The SOC stocks under native vegetation in equilibrium stage, simulated by Century as a period of 5000 years before 1967, were validated comparing it to values related in Sá et al. (2014) and Sá et al. (2001) for the same region.

(vii) Soil texture and bulk density in “site.100” file was adjusted in each simulation, one per benchmark, to assess differences in SOC stabilization caused by soil types and texture.

1.3.7 Statistical analysis, Century validation and maps generation

Differences in soil chemical attributes (SOC, TN, pH, H+Al, Ca, Mg, K, P) trough scenarios (Table 1.2) were tested by an analysis of variance (ANOVA) and when significance at 95% of confidence was met, a LSD test was applied. The relationship between the relative amount of oxides in the clay fraction in the samples and the model bias was obtained by linear regression. The fit between the observed and simulated values were assessed by the R^2 coefficient and by RMSE, EF, CD, RE, M and *t*, the equations used to calculate these statistics can be found in Smith et al. (1997).

Table 1.3: Main input parameters used for calibration of crop.100 files of Century.

Crop files	Century parameters[§]				Simulated C in grain (*cgrain*)	Observed C in grain
crop.100	*PRDX*	*FRCT (1)*	*FRCT (2)*	*HIMAX*		
Native vegetation	235	0	0	0	-	-
Pasture	235	0	0	0	-	-
Rice	290	0.3	0.4	0.5	1.15 (1981)	-
Wheat	540	0.2	0.5	0.4	1.49 (2013)	1.6 (2013)
Soybean	300	0.2	0.3	0.4	1.20 (2013)	1.6 (2013)
Oat	540	0.2	0.5	0.4	-	-
Maize	250	0.05	0.1	0.8	5.50 (2013)	4.8 (2013)
Sucession	Simulated annual C input to soil (*aglivc* + *bglivc*) in Mg Ha^{-1}					
	C input	Biomass input				
Wheat/Soybean	5.2 (2013)	11.5				
Oat/Maize	9.25 (2013)	20.5				
Rice	2.0 (1984)	4.4				
NV	7.7 (1960)	15.5				
Pasture	7.7 (1973)	15.5				

[§] Century parameters: PRDX = potential aboveground monthly production; FRCT(1), FRCT(2) = initial and final fraction of C allocated to the roots, HIMAX = maximum harvest index.

Table 1.4: Key past events occurred on Paiquerê Farm.

Event	Year	Description
1	Until 1966	Native vegetation - Native fields dominated by C4 species
2	1967	Conversion of native field to pasture using “slash and burn” procedure
3	1968 – 1978	Pasture – Native species used for pastureland
4	1979	Conversion of pasture to crops using soil plough procedure
5	1980 – 1984	Rice (with soil tillage) – Cultivated during the first years after the conversion of pastures
6	1985	Conversion to no-till
7	1986 – 2022	Wheat/Soybean, Wheat/Soybean, Oat/ Maize under no-till system

Statistical procedures used: i) Root mean square error (RMSE) - RMSE values less than $RMSE_{95\%}$ means that simulated values follow in the 95% confidence interval of the measurements; ii) Modeling efficiency (EF), positive EF values mean that the simulated values describe the trend in the observations better than the mean of measured data; iii) Coefficient of determination (CD) - a CD higher than 1 means that the simulated values describe the variance of the observations better than the average of the measured data; iv) Relative error (RE) - an RE value smaller than $RE_{95\%}$ means that the simulation bias is within the 95% confidence interval of the measured data; v) Average difference between predicted and measured data (M), M describes the simulation bias; vi) The *t* value verifies if observed and simulated values are significantly different according to Student’s *t* distribution; vii) R^2 - describes the adjustment of the linear regression between observed and simulated values. Calculations of all statistics were undertaken in R v. 3.2.2. Maps of observed and simulated SOC stocks were generated to promote a visual assessment of the simulation bias using spline models in ArcGIS v. 10.2.

1.3 RESULTS

1.4.1 Soil fertility attributes and Century calibration

As the only soil fertility attribute that differed significantly between scenarios was SOC, the variability in the other variables was considered not influencing C storage (Table 1.2). The average soil pH was 4.92 reflecting an acidic soil condition, average exchangeable Ca, Mg, K were 6.22, 1.48, 0.45 cmoc dm^{-3} and available P was 6.53 mg dm^{-3}.

Table 1.5: Relative abundance of clay minerals in all the soil types.

Soil types	Minerals components at clay fraction					Sum of total Oxides
	Kaolinite	Gibbsite	Goethite	Oxides	Others	
	%					
Rodhic Hapludox	14.8	14.9	9.4	46.3	14.7	70.5
Typic Hapludox	18.4	14.4	10.8	42.0	14.3	67.3
Inciptisol Dystrudepth	14.8	20.7	9.1	38.6	16.8	68.4
Inceptisol Anthrept	17.8	15.3	9.6	44.2	13.1	69.0

* Oxides refers to the group of mixed peaks in the 35-40, 50-60 2Θ;
*Others refers to other minerals founded in the X-Ray patterns, quartz and pyrite;
* Sum of total oxides refers to gibbsite + goethite + oxides.

The semi-quantitative mineralogical analysis based on X-Ray patterns indicated that all soil types have similar clay minerals (see Figure 1.2, Table 1.5), approximately 70% of oxides, 15% of kaolinite and 15% of other minerals. The gibbsite relative abundance was higher in InDy, its respective peaks are bigger around 20 2Θ (Figure 2), however it represents just a fraction of unidentified oxides that appears as gibbsite in this soil type (Table 1.5) because in the others XRDs two peaks overlapped in this region.

The biomass input of wheat/soybean succession was 11.5 Mg ha^{-1} year^{-1} while for oat/maize succession the biomass input was 20.5 Mg ha^{-1} year^{-1}, resulting in a three-year input of 43.5 Mg ha^{-1} year^{-1}. The differences between observed and simulated values of C in grains were 0.1, 0.4 and -0.7 Mg ha^{-1} for wheat, soybean and maize respectively (Table 1.3).

1.4.2 Statistics used for model evaluation

A better fit was observed in clayey soils in comparison to sandy clay soils. The mean difference between observed and simulated values for all soils was 10 Mg C ha^{-1} (Table 1.6), however, considering the average of just the clay > 600 g kg^{-1} scenarios, the mean difference was 4 Mg C ha^{-1}, contrasting with 16.26 Mg C ha^{-1} in sandier soils.

No significant difference between observed and simulated values were observed (RMSE values), the *t* statistics also showed the same except for “All data”, and the RE value showed no difference for Heavy Clay-RH, Heavy Clay InDy, Clay InDy and “All data” scenarios (Table 1.6). A positive EF value was observed for Heavy Clay InDy and “All data” scenarios and CD values greater than one was observed in Heavy Clay RH, Heavy Clay InAn and Heavy Clay InDy. All clay scenarios showed a CD value greater than one, excluding Heavy Clay TH, while Heavy Clay InDy presented both (EF and CD values).

The M values were negative for all scenarios excluding Heavy Clay RH and Heavy Clay InDy, meaning that the model underestimated the SOC stocks, and was lower than 10 Mg ha^{-1} for Heavy Clay RH, Heavy Clay TH, Heavy Clay InAn, Heavy Clay InDy and “All data" scenarios. On the other hand, R² values greater than 0.4 were obtained for Clay TH, Clay InDy and "All data" scenarios, contrasting with CD, RE and M that showed a better fit for clay scenarios.

1.4.3 Regression between observed and simulated values

The fit between observed and simulated values showed a R² = 0.41 (Figure 1.3a) and the residuals increased at higher SOC stock values, with a slope of 0.58. However, just considering the average values, the coefficient was R² = 0.83 (Figure 1.3b) and the regression line approached closer to the 1:1 line, with a slope of 1.1. The means fit also showed the regression line under the 1:1 line, with an intercept of -18.4 Mg C ha^{-1}, indicating that the SOC stocks were underestimated by almost 20 Mg C ha^{-1}.

The observed and simulated SOC stocks maps (Figure 1.6) were very similar with respect to the spatial distribution of SOC, however, as observed in the means fit, the SOC stocks were underestimated, especially in Anthrept soils (Figure 1.1).

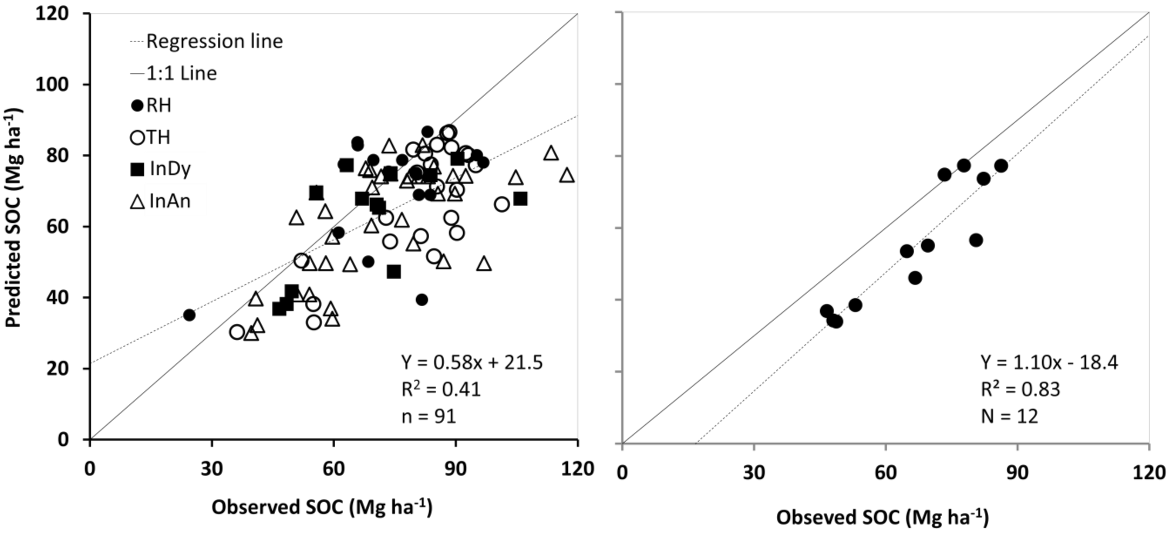

Figure 3: a) Fit between the observed and simulated SOC stocks. b) Fit between the observed and simulated means of SOC stocks.
*RH = Rodhic Hapludox; TH = Typic Hapludox; InDy = Inceptisol Dystrudept; InAn = Inceptisol Anthrept.

1.4.4 Effect of clay and silt content on soil organic carbon stocks

The R² values obtained after performing a linear regression between clay + silt content and SOC was 0.89 and 0.42 respectively for simulated and observed values (Figure 1.4a), the smaller R² of observed values indicate that other factors not related to soil texture are influencing SOC stabilization. The slopes were similar, 0.85 and 0.65 for simulated and observed values, but the intercepts were not, at -0.12 and 25.03 respectively (Figure 1.4a), this combination indicating that at low contents of clay + silt the model underestimated more the SOC stocks. Otherwise, looking to the mean values (Figure 1.4b), the R² of the regressions were 0.89 and 0.94 for observed and simulated values respectively.

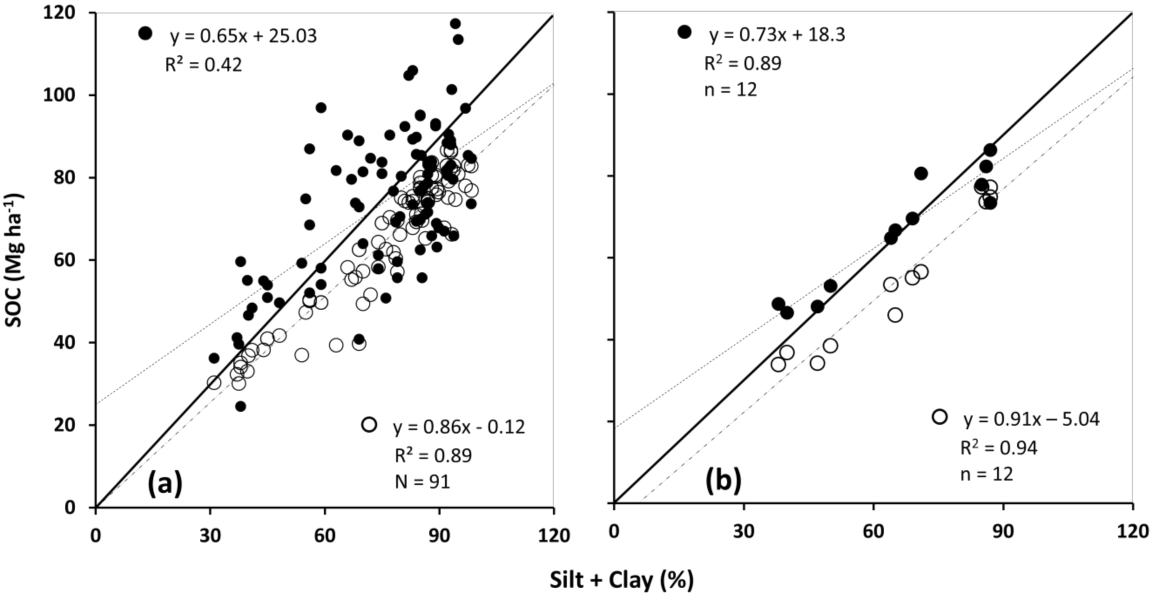

Figure 4: a) Fit between observed and simulated SOC stocks and the clay + silt content observed in benchmarks. b) Fit between the observed and simulated means of SOC stocks and clay + silt content.
*Black circles = Observed values; White circles = Simulated values; Black line = 1:1 line; Gray lines = upper and lower equation lines.

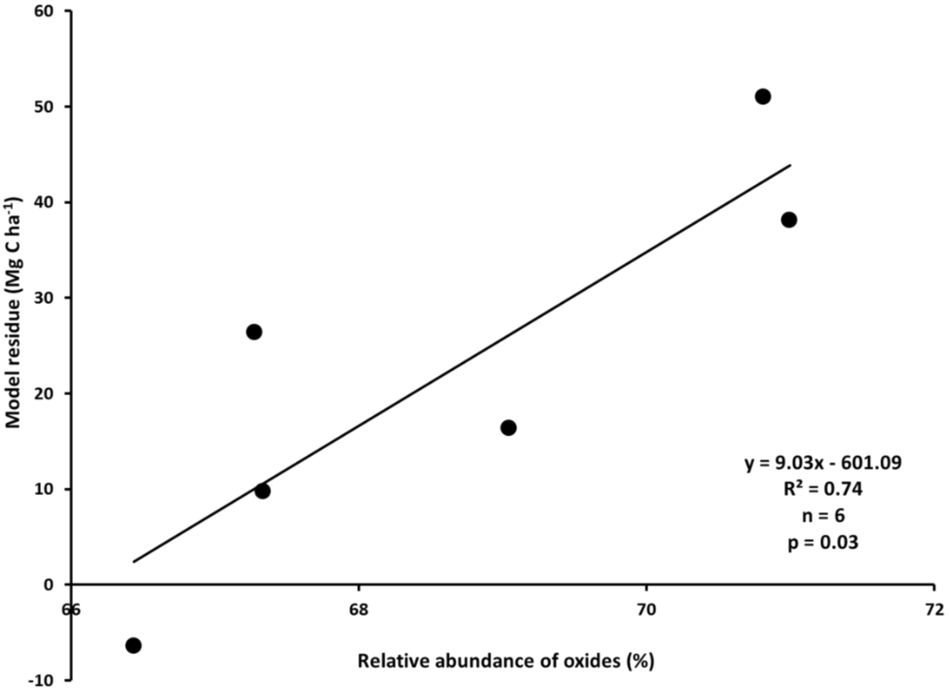

Figure 5: Regression between the relative abundance of oxides in the clay fraction and the model residue.

Even the quantity of oxide minerals in the clay fraction being similar in all soil types, varying between 66 and 71% (Table 1.5), the regression performed showed that with the increase in oxides content the model residue increase (Figure 1.5).

1.4 DISCUSSION

The biomass-C input from crop successions was similar to those reported by Sá et al. (2014) for the same region, emphasizing that the amount of biomass C added was sufficient to enhance the SOC stocks in 0-20 cm layer of the soil profile at the rate of 0.92 Mg C ha^{-1} year^{-1} in 20 years.

The mineralogy of the clay fraction that we found is similar to the mineralogy reported by Gonçalves et al. (2007) for a Rodhic Hapludox of the same region. They found same minerals and reported values of 63, 32 and 5% for oxides, kaolinite, and other minerals respectively. Melo et al. (2007) studying Rodhic and Typic Hapludox in the same state reported 47 - 62% oxides in the clay fraction. Similar mineralogy of Oxisols and Inceptisols for the same study region was also reported by Inda Junior and Kampf (2005). They analyzed 19 Oxisols and 2 Inceptisols, and found the second and third higher concentration of iron oxides for the 2 Inceptisols when compared with the Oxisols. This can be explained by the landscape of the region that facilitates the formation of Oxisols and Inceptisols originated from the same parent material in the catenas (SÁ et al. 2013).

The results of statistical analyses showed that Century was able to efficiently simulate the effect of texture on SOC storage (Table 1.6) The analysis of SOC dynamics models bias usually follow the process described in Smith et al. (1997), which is the case of all the works cited in this paragraph, and so allow a direct comparison. The RMSE values ranged between 11 and 33%, and were similar to values between 10 and 20% reported by Smith et al. (1997), when the authors used 9 different models to simulate SOC storage in 7 long-term experiments in a temperate climate. Bortolon et al. (2011), Tornquist et al., (2009a) and Tornquist et al., (2009b) also used Century model to simulate SOC dynamic during land use change events in a sub-tropical/temperate region in Rio Grande do Sul state, Brazil, found RMSE values of 7.6, 13.2 and 15.9% respectively (n = 10, 7 and 15). Cong et al. (2014) found RMSE values ranging between 5 and 14% while simulate SOC storage in fertilizer trials of corn-wheat cropping systems in a warm-temperate climate in China. The EF values that we found were similar to those reported by Tornquist et al. (2009a) and Lima et al. (2011), 0.11 and 0.29 respectively. The high R² values of the regressions between silt + clay content and SOC stocks (Figure 1.4b) emphasize the importance of clay + silt like the main factor driving SOC stabilization in the farm.

Despite the good fit between observed and simulated values, the absolute values were underestimated. The underestimation of SOC stocks by the Century model in tropical and sub-tropical environments has also been observed in other studies (ARDÖ AND OLSSON, 2003; SILVER et al., 2000; TORNQUIST et al., 2009b). Gijsman et al. (1996) reported that the association between phosphorus (P) and oxides could reduce P availability for the microbes, which would lead to underestimations of SOC stocks because the SOC will be less decomposable. However, the same authors also mentioned that the turnover time of organic P can be faster in tropical and sub-tropical soils in comparison to temperate soils, supplying the necessary P to the microbes for SOM decomposition. The C stock and P contents (Table 1.2) in the soils at Paiquerê Farm is higher than those reported by Tivet et al. (2013) and Sá et al. (2013); and are considered medium to high (WIETHOLTER, 2002), and the nutrient status seems have not influenced SOM decomposition. Besides, the low pH of the farm soils (mean = 4.92) can reduce organic matter decomposition (MOTAVALLI et al., 1994), however as described by the authors, soil pH only exert significant influence on soluble SOC, and cannot explain an underestimation of 10 Mg ha^{-1} in total SOC stocks. Some factors that can explain why this underestimation occurs are: i) the contribution of OM added from roots; and ii) the effect of soil minerals.

Table 1.6: Statistics used to access the fit between observed and simulated SOC stocks in all the scenarios.

Scenario	SOC Mg ha^{-1}		Statistics							
	Observed	Simulated	RMSE (%)	EF	CD	RE	M (Mg ha$^{-1)}$	t	R^2	n§
HC - RH	$77.85^{\pm 11.06}$	$77.88^{\pm 5.36}$	16.19*	-0.42	$4.26^{\pounds}$	2.08*	0.03	0.01*	0.03**	12
HC - TH	$86.33^{\pm 5.84}$	$77.17^{\pm 7.57}$	13.88*	-3.52	0.23	-10.40	-9.15	-1.70*	0.09	15
C - TH	$80.60^{\pm 16.74}$	$56.58^{\pm 5.66}$	33.08*	-2.04	0.39	-27.75	-24.02	-1.09*	0.64**	6
HC - InAn	$82.30^{\pm 17.11}$	$73.71^{\pm 4.22}$	21.42*	-0.12	$3.05^{\pounds}$	-7.28	-8.59	-1.29*	0.17*	18
C - InAn	$66.71^{\pm 15.24}$	$52.33^{\pm 7.3}$	31.12*	-1.03	0.83	-18.59	-14.38	-1.34*	0.03	12
SdC - InAn	$48.68^{\pm 10.36}$	$34.62^{\pm 3.82}$	33.78*	-2.08	0.44	-25.75	-13.46	-0.95*	0.05	5
HC - InDy	$73.41^{\pm 14.28}$	$75.06^{\pm 3.59}$	15.0*	$0.26^{\pounds}$	$12.54^{\pounds}$	4.95*	1.64	0.24*	0.45	5
C - InDy	$69.63^{\pm 19.18}$	$56.32^{\pm 13.34}$	26.76*	-0.10	0.96	-17.58*	-13.31	-1.09*	0.46*	7
All data	$74.23^{\pm 17.65}$	$64.66^{\pm 15.99}$	23.10*	$0.04^{\pounds}$	0.89	-11.31*	-9.57	-6.38	0.41**	91

* The numbers superscript refers the standard deviation.

‡ Texture and soil type: HC – RH, Heavy clay Rhodic Hapludox; HC – TH, Heavy clay Typic Hapludox; C – TH, Clay Hapludox; HC – Ian, Heavy clay Inceptisol Anthrept; C – Ian, Clay Inceptisol Anthrept; SdC – Ian, Sandy clay Inceptisol Anthrept; HC – IDy, Heavy clay Inceptisol Dystrudept; C – IDy, Clay Inceptisol Dystrudept; § n = number of observations.

RMSE = Root mean square error; EF = Modeling efficiency; CD = Coefficient of determination; RE = Relative error; M = Average residue.

The variability of crop yields in the farm (GONÇALVES et al., 2015) could have influenced root-C input, which can explain the bias observed in some parts of the farm (Figure 1.6), especially in Anthrept soils (Figure 1.1). The deep plant root development in sandy clay soils, could explain the higher simulation bias observed in these kinds of soils (Figures 1.4b and 1.6). Daddow and Warrington (1983) and Jones (1983) reported that the growth-limiting bulk density is lower in soils with high content of clay and silt, and even the bulk density values for clay soils related in Daddow and Warrington in their study was 1.4, being higher than those observed at Paiquerê farm, the roots development in sandy-clay soils on the study site could have less restriction. Specifically, the underestimation in tropical sandy clay soils by about 45% was reported by Silver et al. (2000), this kind of finding is poorly reported in the literature in part because it just appear when simulate sandy and clay soils with the same model calibration. The authors attributed the underestimation to possible non-mineral C stabilization mechanisms, not considered by Century. Soil nutrients, water and plants feedbacks may also have contributed as the vegetation dynamics exert influence in C cycle and roots growth can be greater in tropical sandy clay soils looking for water and available P (NEPSTAD, 1994). The underestimation of SOC in sandy clay soils was also reported by Foereid and Høgh-Jensen (2004), simulating non fertilized crop rotation experiments in temperate soils, however in simulating fertilized crop rotation the underestimation not occur. Lugato et al. 2007 reported a good fit between observed and simulated SOC stocks in a short-term experiment in north Italy, the slow and the passive SOC pools were measured and manually adjusted in the model, suggesting that the source of underestimation can be in this two pools.

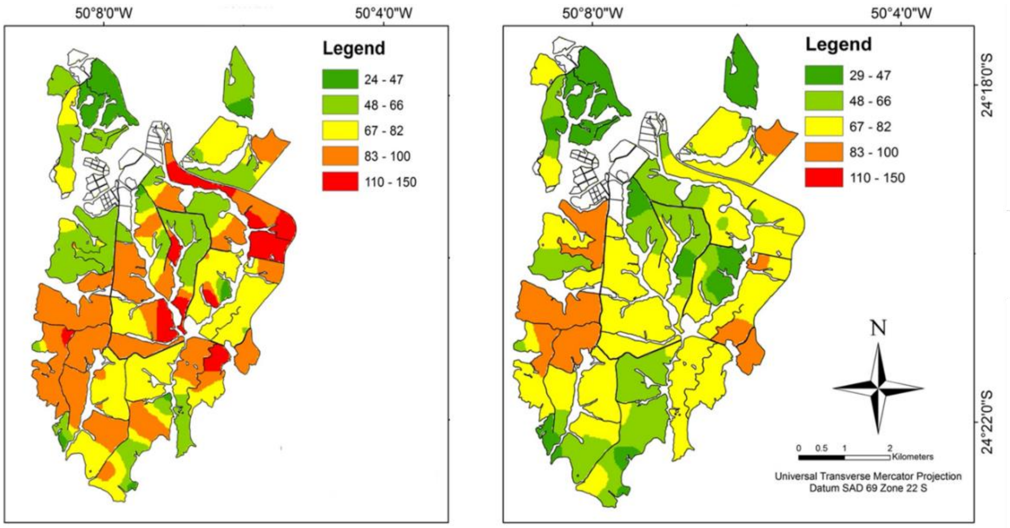

Figure 6: Maps of spatial distribution of measured (left) and simulated (right) SOC stocks in Mg ha-1.

Other factor that may have influenced SOC stabilization is the type of clay minerals. The x-ray patterns confirmed that the main clay mineral types such as kaolinite, gibbsite and goethite (Figure 1.2), are different than the minerals observed in smectitic soils, from temperate ecosystems where Century was developed. In the 2:1 clays, the main mechanism for C stabilization is the cationic bond formed with Ca, and for Fe and Al (hydro) oxides through ligand exchange (SPARKS, 2003), especially in acidic soils (pH 4.92), that is lower than goethite point of zero charge (8.1), resulting in high positive charges on iron and aluminum oxides. This implies that the bond strength between C and oxides is higher than those between C and 2:1 clays, thus explaining the lower C desorption and mineralization in oxide soils compared to 2:1 clays (SAIDY et al., 2013; SAIDY et al., 2012), also the higher stabilization of molecules with high molecular weight (FENG et al., 2005).

A close relationship between the relative abundance of oxides in the clay fraction and the model residual supports this argument and the slope of the regression (9.03, Figure 1.5) corroborate to explain the standard deviation in measured SOC stock for each scenario (Table 1.6). The oxides abundance had low variation among soil types and had limited influence in the model bias when compared to the silt+clay content. Even so, the effect of Fe and Al (hydro) oxides on stabilization of SOC, should have contributed to the general underestimation of the farm SOC stocks. The influence of clay minerals on SOC stabilization has been reported by many authors (KAISER and GUGGENBERGER, 2003; PARFITT et al., 1997; SAIDY et al., 2013). However, due to the difficulty in developing mathematical representations that simulate the C allocation to the passive compartment of the SOC in the presence of different soil clay minerals (considering each mineral’s individual contribution and interactions to C stabilization) these variables are not simulated by Century.

Other important aspect to mention is the pronounced effect of non-crystalline minerals on C stabilization. Torn et al. (1997) reported a positive relationship between the amount of non-crystalline minerals and SOC content along the last 150000 years in a Hawaiian chronosequence, giving more importance to soil mineralogy than primary productivity driving the SOC contents, the high capacity of non-crystalline minerals to store SOC is also supported by other works (CROW et al. 2015; PAUL et al. 2012). Gamboa e Galicia (2012) related that the association between organic compounds and non-crystalline minerals explain C storage in soil horizons and other authors associated the importance of non-crystalline minerals in the stabilization of recent added SOM (GAMBOA and GALICIA, 2012; PAUL et al. 2012). Thus, the relation between total and amorphous oxides and the model residuals perhaps could get a better fit and differences between soil types might have been more pronounced.

The general underestimation of SOC stocks promoted by the oxides, as reported by Leite and Mendonça (2003) can also be seen in the figure 1.3b. Otherwise, it was expected that soils with high content of clay and silt would present higher simulation bias, which was not observed in our study. The possible reasons for Century underestimations of SOC stocks in sandy clay soils described earlier helps to explain these results. Zinn et al. (2007), reported a higher C content in the clay fraction of soils with less than 200 g clay kg^{-1} (50 g SOC kg^{-1} clay), when compared to soils with 600 g clay kg^{-1} soils (about 20 g SOC kg^{-1} clay). Therefore, the relationship between SOC stabilization and clay + silt content can be nonlinear, which is also supported by the different bias observed in Figure 1.4a. Beyond the individual effect of oxides, the crystallinity of the clay minerals and the mineral interactions can also contribute to the SOC stabilization. Saidy et al. (2013) reported that goethite can cover kaolinite increasing the C stabilization capacity of soils from 2 to 6 mg C g^{-1} clay and also decreasing the desorption of C from 10 to 5%. However, the same phenomenon was not observed with the cover of illite by goethite. Consequently, the SOC stabilization by clay minerals is not a function of just the SSA of clay + silt minerals.

Alternative models that aim to simulate the Oxisol properties have been proposed. Zinn et al. (2007) proposed an equation to predict SSA of Oxisols.

$$\text{SSA } (m^2\, g^{-1} \text{ soil}) = 0.0581(\text{clay}) + 0.0594(\text{silt}) - 0.271(\text{SOC}) \qquad (11)$$

$(P < 0.001, R^2 = 0.97, n = 27)$

Conversely, the negative effect of SOC on SSA of Oxisols and the SOC stabilization dependence on clay content could improve Century simulations by reducing bias in Oxisols, specially with lower clay and silt contents.

1.5 CONCLUSION

Century was able to simulate the SOC storage in all investigated soil types and textural classes with differences due to soil texture affecting more the simulation bias than soil types. However, the model underestimated SOC stocks in almost all soils. The simulation bias was greater for sandy clay soils suggesting that the relation between clay + silt content and SOC storage can be nonlinear. We observed an increase in the model residual with increase in oxides relative abundance in the clay fraction, consequently mineralogical control on SOC stabilization, especially the high capacity of Fe and Al (hydro) oxides, can improve Century simulations. Further research that aims to quantify the effect of Fe and Al (hydro) oxides on SOC stabilization can provide new insights on these mechanisms.

1.6 ACKNOWLEDGMENTS

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CHAPTER 2 – SOIL CARBON INVENTORY TO QUANTIFY THE IMPACT OF LAND USE CHANGE TO MITIGATE GREENHOUSE GAS EMISSION AND ECOSYSTEM SERVICES

Abstract: Currently the land use and land use change (LULUC) emits 1.3 ± 0.5 Pg carbon (C) year^{-1}, equivalent to 8% of the global annual emission. Techniques such as low carbon agriculture has been developed to reduce greenhouse gases (GHG) emissions from LULUC sector. The objectives of this study were to quantify 1) the impact of LULUC on GHG emissions in a sub-tropical region and 2) the role of conservation agriculture to mitigate GHG emissions. We develop a detailed IPCC Tier 2 GHG inventory for the Campos Gerais region of southern Brazil that has large crop area under long-term conservation agriculture with high crop yields. The inventory accounted for historical and current emissions from fossil fuel combustion, LULUC and other minor sources. We used Century model to simulate the adoption of best management practices, to all croplands in the region from 2017 to 2117. Our results showed historical (1930 – 2017) GHG emissions of 412.18 Tg C, in which LULUC contributes 91% (376.2±130 Tg C), the uncertainties range between 13 and 36%. Between 1930 and 1985 LULUC was a major source of GHG emission, however from 1985 to 2015 fossil fuel combustion became the primary source of GHG emission. Forestry sequestered 51.7 ± 23.9 Tg C in 0.6 Mha in 47 years (1.8 Tg C Mha^{-1} year^{-1}) and no-till sequestered 30.4 ± 23.9 Tg C in 1.9 Mha in 32 years (0.5 Tg C Mha^{-1} year^{-1}) being the principal GHG mitigating activities. The model predictions showed that best management practices have the potential to mitigate 13 years of regional emissions (330 Tg C in 100 years) or 105 years of agriculture, forestry and livestock emissions (40 Tg C in 100 years) making the agriculture sector a net C sink. As most of the future land use change to meet the global food demand is expected in sub-tropical regions, our methodology can be used as a model to create C inventories for supporting public policies aiming to mitigate GHG emissions.

Key words: Best management practices; carbon; sub-tropical region; IPCC Tier 2; Century model; agriculture, forestry and land use change

List of acronyms: AFOLU, Agriculture, forest and other land use; C, Carbon; EU, European Union; GHG, Greenhouse gases; IPCC, International panel on climate change; LU, Land use; LUC, Land use change; LULUC, Land use and land use change; OECD, Organization for economic co-operation and development; SOC, Soil organic carbon; UK, United Kingdom; US, United States of America.

2.1 INTRODUCTION

Currently, main drivers of GHG emissions are fossil fuel combustion and cement production (9.8 ± 0.5 Pg C $year^{-1}$) comprising 82% of the global annual emissions (HOUGHTON, 2014; LE QUÉRÉ et al., 2015; PACHAURI et al., 2014). Land use and land use change that emits 1.3 ± 0.5 Pg C $year^{-1}$ or 8% of current annual emissions (HOUGHTON, 2014; LE QUÉRÉ et al., 2015), has been receiving comparatively less attention from policy makers and the scientific community. The first time that soil C and agriculture were at COP21 agenda was in 2015 (LAL, 2016). The historical emissions from LULUC are estimated to be 320 Pg C since the beginning of agriculture or 136 Pg C from 1750 to 2010 (HOUGHTON et al., 2012; RUDDIMAN et al., 2015), comprising the largest historical GHG source. In addition, historical emissions from vegetation slash and burn comprises 67 Pg C, representing 10.8% of the C stock in terrestrial vegetation (LAL, 2004; LE QUÉRÉ et al., 2015; SÁ et al., 2017). On the other hand, LULUC plays an important role in providing land for agriculture, pasture, forestry, and key activities to human development. Currently, 40% of the Earth surface is cultivated land, and it will be difficult for this land area to increase to meet the needs of growing human population (FOLEY et al., 2011; LAL, 2016; OSTLE et al., 2009).

Greenhouse gases inventories are being developed in many countries to understand GHG mitigation options. Ding et al. (2017) performed a life cycle assessment of the energy production in all China provinces. They found the provinces of Jiangsu and Shandong as the more dependent on thermal power. Su et al. (2016) using IPCC methodology performed a GHG emission inventory for all EU countries. They report Germany, UK and France as the higher, and Cyprus, Malta and Latvia as the lower GHG emitters. In the same way, Diana et al. (2017) mapped the C footprint of EU regions. They reported UK having the highest C footprint and Bulgaria and Romania with the lowest C footprint. The variable that most explained higher C footprints was income. O'Keeffe et al. (2017) performed a regional life cycle inventory approach for biodiesel production in Germany and reported 13 – 31% greater mitigation potential compared to Renewable Energy Directive reports. All These results can be used to develop strategies aiming to reduce GHG emissions.

Other studies compared different methodologies aiming to improve the accuracy of GHG inventories. Li et al. (2016) compared two methods to measure ecosystems C balance, net biome productivity and soil C inventory in northern Japan. Their result indicated an increase in net primary production and soil C between 1959 and 2011. Nemecek et al. (2016) used two approaches to project N_2O, NH_3 and NO_3 emissions in an IPCC Tier 1 inventory.

They reported significant changes especially for nitrate dynamics and N_2O emissions, indicating improvement potentials in IPCC C inventory method. Caro et al. (2017) performed an inventory accounting CO_2 production and consumption, highlighting China as a big exporter and US as a net importer of CO_2.

For the LULUC sector, soil and ecosystem C inventories have been largely performed for global scenarios (HOUGHTON, 2014; LAL, 2004; LE QUÉRÉ et al., 2015) and OECD countries (GREGORICH et al., 2005; GUO et al., 2006; LUGATO et al., 2014). Lugato et al. (2014) used Century model to perform an inventory of European SOC stocks. They reported high SOC stocks in UK and Netherlands wetlands with mean inventory uncertainty about 36%. Viscarra Rossel et al. (2014) performed a SOC inventory for Australia and found higher values than previously reported (25 Gt C in 0-30 cm soil depth). Zhou et al. (2017) performed a detailed biomass burning C emissions inventory in China. They reported domestic burning associated with maize, rice and wheat straw was driving total biomass burning emissions.

GHG inventories play a fundamental role in providing a basis for the development of public policies. However, it is rarely being conducted for developing countries (e.g. Southeast Asian, African, and South American). In South America, where agriculture plays a major role in GHG emission and mitigation, regional inventories can be of great importance. Gloor et al. (2012) calculated the GHG emissions from South America and reported that the continent was a net source of C (0.3 to 0.4 Pg C year^{-1}) in the 1980s, and close to neutral (0.1 Pg C year^{-1}) in the 1990s. They attributed the neutral emission in the 1990s to the growth of old forests. Esteves et al. (2017) performed a GHG inventory of tallow biodiesel production and reported less emission (43.2 Kg CO_2 ha^{-1} year^{-1}) in comparison to soybean biodiesel production (50.2 Kg CO_2 ha^{-1} year^{-1}). Recently, Sá et al. (2017) reported that the large-scale adoption of low C agricultural best management practices in South America can contribute to mitigate 8.24 Pg C between 2016 and 2050 (0.08 to 0.28 Pg yr^{-1}), 25.2% of global LULUC annual emissions. Besides other few reports (CERRI et al., 2010; MELLO et al., 2014; VILLARINO et al., 2014), detailed carbon inventories at national and regional scales are rare.

In parallel with the GHG inventories development, forestry and low C agriculture practices have been reported as promising tools to mitigate GHG emissions (PACHAURI et al., 2014). Sá et al. (2017) estimated that the contribution of forestry sector can be up to 3.17 Pg C between 2016 and 2050. In addition, no-till systems can contribute to mitigate 2.01 Pg C. Particularly no-till fits well in the SOC 4 per mille concept, which was introduced in the COP21 United Nations convention. This concept proposed to increase the SOC stocks by 0.4% per year during the next 20 years as a strategy to promote C sequestration (LAL, 2016).

This way, is possible to save time for the development of new technologies aiming to mitigate GHG emissions. However, lack of observational data leads to uncertainties related to the potential of conservation agriculture techniques to sequester SOC and mitigate GHG emissions (POWLSON et al., 2014).

These uncertainties are related as one of the main issues holding the development of GHG markets (GREN and AKLILU, 2016). On the other hand, although regional benefits of carbon sequestration are related to its monetization, benefits like wildlife preserve and control of soil erosion can be considered (FENG et al. 2004). Especially control of soil erosion can increase water quality reducing costs of water treatment (FOSTER et al. 1987). In addition, studies have reported improvement of agronomic yield and profitability by fertilization reduction and increase of nutrient and water availability following increase in soil carbon content (BHARDWAJ et al. 2011; GONÇALVES et al. 2017b).

In this study, we developed a detailed GHG inventory for the region of Campos Gerais do Paraná, Southern Brazil. This region has large area under long-term continuous conservation practices (BRÜGGEMAN, 2013, CASTROLANDA, 2015, FRÍSIA, 2016). Our GHG inventory accounted for the emissions from fossil fuel combustion and LULUC sector as well as historical contribution of conservation agriculture to mitigate GHG emissions. In this way, we track the GHG emission patterns of a sub-tropical region during its development, highlighting the effect of LUC. In addition, we calibrated the Century model (PARTON et al., 1987), using the observations from Paiquerê farm. This farm has been managed for 30 years under continuous “best management practices” and characterized by high crop yields and crop rotation intensity (GONÇALVES et al., 2017a). We used the Century model to simulate the adoption of best management practices in entire croplands of the region.

2.2 MATERIALS AND METHODS

2.2.1 Study area

We conducted this study in Campos Gerais region, located in Paraná state, Southern region of Brazil (Figure 2.1). This region comprises 3.2 million ha between the First and Second Paraná plateaus divided by the Devonian Escarpment (INDE, 2010). It comprises 27 municipalities, Ponta Grossa being the biggest population and economic center with 341,130 habitants, the whole region has 1.1 million habitants (IBGE, 2016). In Paraná state’s Gross Domestic Product, agriculture represents 9%, industry represents 21%, and services sector represents 70% (IPARDES, 2016).

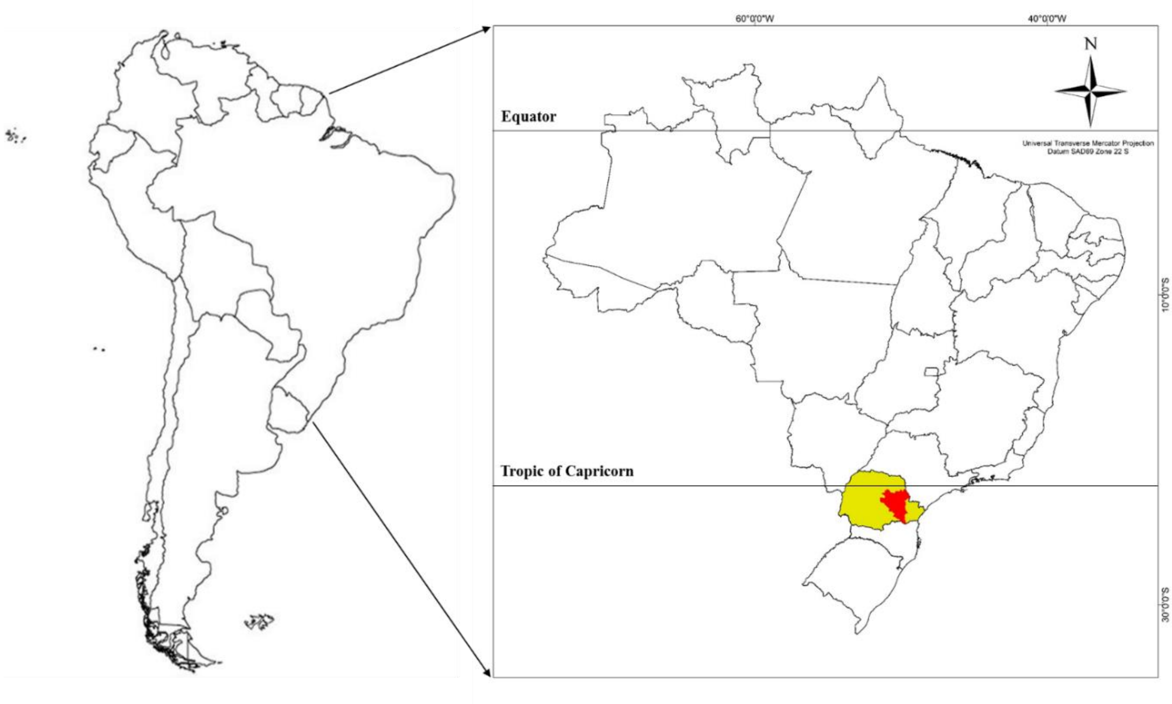

Figure 7: Localization of Brazil, Paraná state and Campos Gerais region.

The altitude ranges between 700 to 1290 m (MELO et al., 2007) and the climate is classified as sub-tropical humid, Cfa and Cfb according to Köppen classification (MAACK, 1981). The mean annual temperature ranges between 17 °C in the South and 22 °C in the Northern part, and the annual precipitation ranges between 1200 mm in the plateaus and 1800 mm in the Devonian Escarpment (MELO et al., 2007).

The relief of the study region is slightly undulated, with slope ranging from 0 to 20% in most areas but going up to 50% in the Devonian Escarpment (MINEROPAR, 2006; INDE, 2010). The soil types observed in the region are classified as Oxisols, Inceptisol, Ultisols and Entisols according to USDA Soil Taxonomy (SOIL SURVEY, 2014). Histosols (SOIL SURVEY, 2014) dominate the lower part of the landscape along the river borders.

2.2.2 Brief history of land use change in the region

The cultivation of the region started in the 18th century when its prairies were used for cattle feed during transportation (Figure 2.2). In the 19th century, villages grew to cities and in 1890s, Ponta Grossa had 4774 habitants (PONTA GROSSA, 2016). In the 1930s, a large portion of native vegetation was converted to pastures (ITCG, 2010). Following the economic development and European migrations, mainly Germans, Polish, Russians and Italians, the population grew and in 1970 Ponta Grossa had 126940 habitants (PONTA GROSSA, 2016).

During the 1970s, great portion of region pastures were converted to croplands and planted forests (ITCG, 2010).

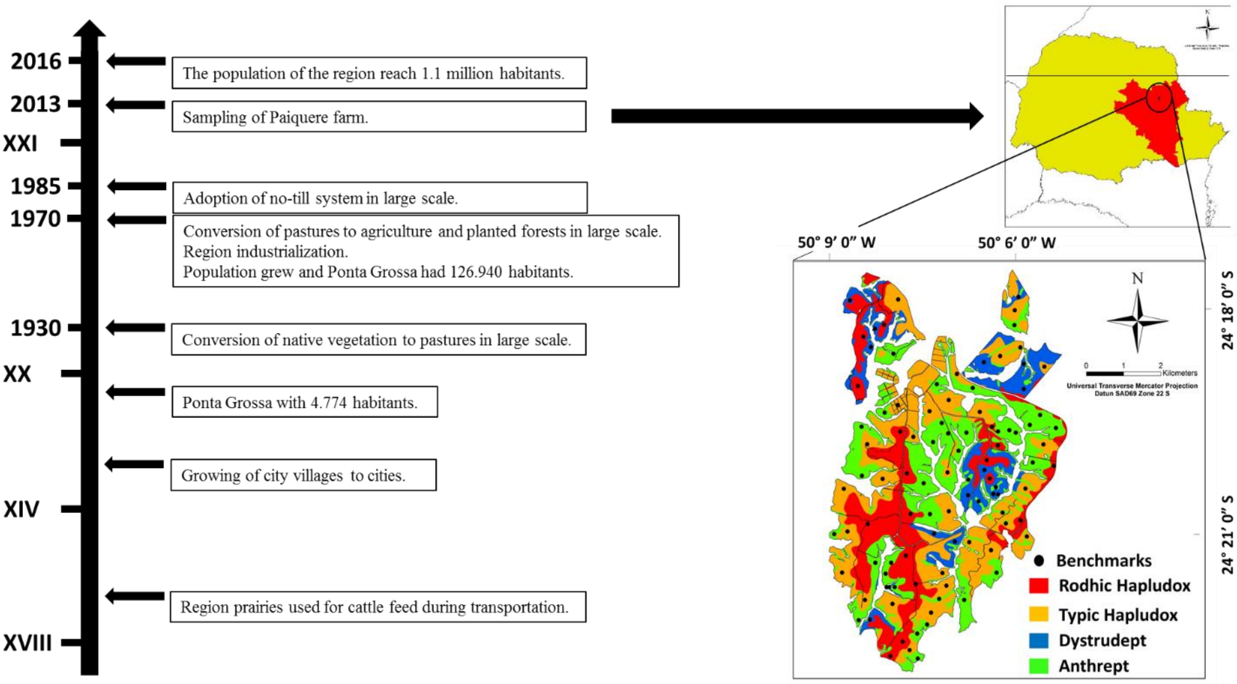

Figure 8: Main events occurred in Campos Gerais region, Paiquerê farm, soil types and benchmark locals.

The conventional soil tillage, largely adopted in the region led to disruption of soil aggregates and massive reduction in soil C stocks (BORGES, 1993; TIVET et al., 2013). High soil erosion rates were observed due to high precipitation in summer coupled with undulated landscape and full soil tillage. Adoption of no-till system started in 1970s and adopted at large scale in the region in 1980s. No-till agriculture contained the rate of soil erosion and increased the SOC levels ultimately making the agriculture profitable (BORGES, 1993). In addition, industrialization in the region started in 1970s (BRAGUETO, 1999) which led to exponential growth of the population reaching 1.1 million in 2016.

2.2.3 Farming system site and best management practices

To assess the potential of conservation agriculture to mitigate GHG emissions, we selected the Paiquerê farm. This farm is located in Campos Gerais region (Figure 2.2) and managed for 30 years under continuous best management practices. In this study, best management practices means according Tilman et al. (2002) agricultural best management practices that meet current and future societal needs for food and fiber, for ecosystem services, and for healthy lives, and that do so by maximizing the net benefit to society when all costs and benefits of the practices are considered. In addition, the farming system is based on the three pillars of conservation agriculture: permanent soils cover; crop rotation; no-till associated with high intensive crop rotation and high crop yields. It also includes the use of broad-graded terraces to control the runoff of rainwater. The mean of crop yield for the period of 2001 to 2013 was 3.3 Mg ha^{-1} for wheat, 3.7 Mg ha^{-1} for soybeans and 10.4 Mg ha^{-1} for maize, and the mean biomass input to soil was 14.5 Mg ha^{-1} year^{-1} (GONÇALVES et al., 2017a). The main difference of this system compared to the standard used in the region is the crop rotation that comprises three successions, wheat (Triticum aestivium L.)/ soybean (Glycine max L.), wheat/soybean for the second year and Oat (Avena sativa L.)/ Maize (Zea Mayz L.). The average biomass input for wheat/soybean was 11.5 Mg ha^{-1} year^{-1} and for oat/maize system the biomass input was 20.5 Mg ha^{-1} year^{-1}, which provided the mean annual biomass input of 14.5 Mg ha^{-1} year^{-1} (GONÇALVES et al., 2017a). In addition, the productivity of this farm (average of the last five years) is higher than the regional average. The productivity of maize is 10.5 Mg ha^{-1}, soybean is 4.0 Mg ha^{-1} and wheat is 3.6 Mg ha^{-1}, representing 26, 29 and 23% higher than those of the regional averages, respectively. The use of a production farmland in our study helps to make our conclusions more reliable as it avoids the limitations of adopting research plot results to general croplands.

2.2.4 Greenhouse gases inventory approach

To quantify the historical GHG emissions of the region we adopted a detailed inventory based on IPCC tier 2 approach (PACHAURI et al., 2014). We summarize the adopted approach below:

We divided the Campos Gerais GHG emission (CG GHG_{em}) sources in three groups, LULUC (LULUC_{em}), fossil fuel (Fossil fuel_{em}) and others (Others_{em}) (Eq. 1). As the region does not have cement production facilities this source of emission was not considered.

$$\text{CG GHG}_{em} = \text{LULUC}_{em} + \text{Fossil fuel}_{em} + \text{Others}_{em} \qquad (1)$$

The LULUC_{em} include emissions from land use change (LUC_{em}) and Land use (LU_{em}) (Eq. 2). Emissions from LUC include vegetation slash and burn, wetland draining and SOC mineralization when the land cover was converted to croplands from native vegetation, forests or pastures (Eq. 3). In this case, we used the emission factors of IPCC (PACHAURI et al., 2014), and for LUC we considered the difference between the original and converted ecosystems C stocks as emitted C. Emissions due to LU (Eq. 4) change from forestry and croplands include SOC emissions due to soil tillage, C offset by vegetation growth and SOC sequestration in no-till system. We also included emissions from farm and forestry activities (nitrogen fertilization, liming, pesticides and fossil fuel emission from machinery) and livestock farming. The soil tillage and no-till based system emission factors, -1.6 Mg ha^{-1} $year^{-1}$ and 0.6 Mg ha^{-1} $year^{-1}$ respectively, were obtained from Sá et al., (2017), Sá et al. (2014) and Zanatta et al. (2007). The emission from livestock comprises enteric fermentation, estimated at 0.33 Mg C $year^{-1}$ $head^{-1}$, and manure management estimated at 0.05 Mg C $year^{-1}$ $head^{-1}$ Cerri et al. (2010). The emission factors 35.8 and 5.8 Kg C_{eq} ha^{-1} $year^{-1}$ were used for soil tillage and no-till based systems, respectively. Similarly, for forestry, 0.02 Mg C_{eq} ha^{-1} $year^{-1}$ was used. These emission coefficients were obtained from Lal (2004) and Cerri et al. (2010).

$$\text{LULUC}_{em} = \text{LUC}_{em} + \text{LU}_{em} \tag{2}$$

$$\text{LUC}_{em} = \text{Vegetation slash and burn}_{em} + \text{Wetland draining}_{em} + \text{SOC}_{em} \tag{3}$$

$$\text{LU}_{em} = \text{Soil tillage SOC}_{em} - \text{No-till SOC}_{seq} - \text{Vegetation growth}_{seq} + \text{Farm and forestry}_{em} + \text{Livestock}_{em} \tag{4}$$

Fossil fuel emissions (Eq. 5) include household emissions from liquid petrol gas and lightning kerosene (Eq. 6), transport emissions from gasoline, diesel, natural gas and aviation gasoline (Eq. 7) and industrial emissions from natural gas (Eq. 8). The others group accounts for C offset from waste recycle (Eq. 9).

$$\text{Fossil Fuel}_{em} = \text{Household}_{em} + \text{Transport}_{em} + \text{Industrial}_{em} \tag{5}$$

$$\text{Household}_{em} = \text{Liquid petrol gas}_{em} + \text{Lightning kerosene}_{em} \tag{6}$$

$$\text{Transport}_{em} = \text{Gasoline}_{em} + \text{Diesel}_{em} + \text{Natural gas}_{em} + \text{aviation gasoline}_{em} \tag{7}$$

$$\text{Industrial}_{em} = \text{Natural gas}_{em} \tag{8}$$

$$\text{Others}_{em} = \text{Waste recycle}_{seq} \tag{9}$$

To calculate the historical GHG emissions from LULUC, we obtained maps of native vegetation and land cover change from ITCG (2010) and the historical data of the Campos Gerais region cattle flock from IPARDES (2017). For the organization of the information and visualization of the results, we used the software ArcGIS v. 10.4.1. (ESRI, 2017). We calculated the ecosystem C stocks as a sum of the vegetation, comprising both above and belowground C, and soil C stocks (Eq. 10).

$$\text{Ecosystem C stocks} = \text{Aboveground biomass C} + \text{Belowground biomass C} + \text{SOC} \tag{10}$$

The limit of C storage in planted forest biomass was considered to be reached in 30 years, period in which the proportion of small and large trees stabilizes. Thus, the biomass C stocks were considered equivalent to a 15 years forest (*Pinus sp. L.* and *Eucalyptus sp. L'Her*). The saturation point for SOC stocks was considered 80 Mg C ha^{-1} for agriculture soils (GONÇALVES et al., 2017a), 140 Mg C ha^{-1} for soils under planted forests, and 165.3 Mg C ha^{-1} for soils under native forests (HARTMANN et al., 2014). The amount of C in above and belowground vegetation and SOC stocks for all ecosystems, natural and production systems, were obtained from literature review and the sources are described in the tables 1, 2, 3 and 4.

We obtained the data of annual regional consumption of all kinds of fossil fuels from ANP (2017) and Ponta Grossa (2017) to calculate fossil fuel and other emissions. The coefficients used to calculate the CO_2 emissions from gasoline (33.72 Kg L^{-1}), diesel (38.43 Kg L^{-1}), natural gas (1.87 Mg m^{-3}), airplane gasoline (31.59 Kg L^{-1}), LPG (23.52 Kg L^{-1}) and lightning kerosene (36.92 Kg L^{-1}) were obtained from U.S. Agency information administration - EIA (2017, https://www.eia.gov/energyexplained/?page=environment_about _ghg). When the historical uses of fossil fuels and waste recycle were not available, the values were estimated using population and vehicle units growth data (IBGE, 2016; IPARDES, 2017).

We calculated the amount of recycled waste as a percentage of total waste production in the region (Ponta Grossa, 2017, Curitiba, 2017), and the amount of CO_2 saved was 3.15 Mg CO_2 Mg^{-1} of recycled waste (EIA, 2017). All GHGs (CH_4, N_2O and CO_2) values were converted to CO_2 and C equivalent to facilitate comparisons between sectors and offset by soil C sequestration. We used the conversion factors of 25 and 298 to convert CH_4 and N_2O emissions into CO_2 and 0.36 to convert CO_2 into C equivalent (EIA, 2017).

We calculated the GHG emission and ecosystem C stocks for specific periods aiming to assess the most important events that occurred in the Campos Gerais region (Figure 2.2). These periods were: before 1930, 1930 – 1970, 1970 – 1985, 1985 – 2017 and the C balance was calculated as the difference between emitted and sequestered C by the end of each period (Eq. 11).

$$\text{CG Carbon balance} = \text{Total C stocks} - C_{em}\text{ before 1930} + C_{em}\text{ 1930 – 1970} + C_{em}\text{ 1970 – 1985} + C_{em}\text{ 1985 – 2017} \tag{11}$$

In 2013, we defined 98 locations as benchmarks (Figure 2.2) comprising all soil types and texture gradients of the farm (GONÇALVES et al. 2017a). We collected bulk soil samples with an auger and 5 x 5 cm core rings from two depth intervals, 0-10 and 10-20 cm. The SOC content of soil samples were analyzed using dry combustion process of a CN analyzer (Tru Spec LECO, 2006 St. Joseph, EUA) and the bulk density was obtained by the core method (GROSSMAN and REINSCH, 2002). The SOC stocks were calculated according to the Eq. 12.

$$\text{SOC (Mg ha}^{-1}\text{)} = \text{Bd (Mg m}^{-3}\text{)} * \text{d (m)} * \text{SOC (kg kg}^{-1}\text{)} * \text{SA (m ha}^{-1}\text{)} \qquad (12)$$

Where: Bd =Bulk density, d = soil depth and SA = surface area.

We used the collected soil samples and other environmental data to calibrate the Century model (PARTON et al., 1988). Briefly the calibration procedure followed the sequence:

i) Initialization and calibration of “Crop.100” files using mean crop yields for maize, soybean and wheat from farm’s database. We used indices “yield/shoot” and “root/shoot” obtained from Sá et al. (2014) and Villarino et al. (2014) to estimate the amount of root and shoot biomass-C input from all the crops. The biomass-C input from black oats and rice (cultivated in the farm on 70’s) were obtained from the literature (FAGERIA, 2000, SÁ et al., 2014);

ii) Validation of grain yield, root and shoot C simulations. For this the output variables of economic yield of C in grain + tubers for grass/crop “cgrain”, C in aboveground live biomass for grass/crop, “aglivc” and C in belowground live biomass for grass/crop, “bglivc” were used;

iii) Simulation of SOC stocks for the 98 farm benchmarks that presented different soil textures. It presented a mean error of -9.57 Mg ha^{-1} (13%), indicating a good fit between observed and simulated values. A detailed description of the farm crop rotation system, soil sampling and analysis process and Century model calibration can be found in Gonçalves et al. (2017a).

2.2.5 Future projections, carbon offset and uncertainty analysis

We used the Century model to make projections of C offset considering the adoption of best management practices in all the Campos Gerais region croplands in 2017. For the projections we derived the C input trough soil from the farm’s crop rotation (Paiquere farm calibration as described before) and set the initial SOC stocks as the mean for the region croplands in 2017. The result was then multiplied for the total croplands area of the region to obtain the new SOC stocks. We simulated the SOC stocks in periods of 50 years (2017 to 2067, 2067 to 2117) to assess the impact of best management practices to offset GHG emissions. To calculate the GHG mitigation potential we assumed no more LUC and emissions from LU, fossil fuel and other sectors to be constant between 2017 and 2117. The projections didn't aim to simulate the future development of the region but analyze how much C can be saved with the adoption best management practices.

For the calculation of the uncertainties in the GHG inventory, we used the standard deviation propagation equation (Eq. 13).

$$SD = \sqrt{\sum_{i=1}^{n} (\sigma_i)^2} \tag{13}$$

Where: SD is the final standard deviation and σ_i is the standard deviation of the $_i$ C stock that is being summed.

The uncertainty associated with the Century model simulations was estimated using the empirical method described in Ogle et al. (2007) and Monte Carlo simulations (OGLE et al., 2010; PACHAURI et al., 2014). Briefly: i) Multiple linear regression was performed fitting measured SOC stocks as a function of simulated SOC (for the 98 bechmarks), soil texture and soil bulk density (Eq. 14) (GONÇALVES et al., 2017a).

$$\text{Measured SOC} = \beta_0 + \beta_1 * \text{Simulated SOC} + \beta_2 * \text{Silt} + \beta_3 * \text{Sand} + \beta_4 * \text{Clay} + \beta_5 * \text{Bulk density} \tag{14}$$

ii) The variables that presented a p value < 0.05 were tested for normality with Shapiro-Wilk test and used for uncertainty calculation. iii) The means vector (μ) and covariance matrix (σ) of the remaining variables were used to generate a multivariate normal distribution and 100 simulated samples (n) for the selected variables. iv) The intercept and coefficients of the multiple linear regression and the simulated variables (Sim var.) were used to run the equation 100 times (Eq. 15).

$$\text{Estimated SOC}_{(1|100)} = \beta_0 + \beta_1 * \text{Sim var. } 1_{(1|100)} + \beta_2 * \text{ Sim var. } 2_{(1|100)} + \beta_3 * \text{ Sim var. } 3_{(1|100)} + \beta_4 * \text{ Sim var. } 4_{(1|100)} + \beta_5 * \text{ Sim var. } 5_{(1|100)} \tag{15}$$

v) The 95% confidence intervals were generated using the 100 values of Estimated SOC according to Eq. 16.

$$\mu \pm 1.96 * \sigma/\sqrt{n} \tag{16}$$

Where: 1.96 is the standard z value associated with 95% confidence interval; σ is the standard deviation of Estimated SOC and n is the number of replications (100). For the uncertainties calculation we used the software R v. 3.4.0 (R CORE TEAM, 2017).

2.3 RESULTS

2.3.1 Native vegetation in Campos Gerais region

The Campos Gerais region has a total land surface area of 3.2 million ha (Table 2.1). Out of this land area, 65% of has forests, 31% has grasslands, 3% has wetlands and 1% has Brazilian acid savannas, the Cerrados (Figure 2.3). The estimated total ecosystem C in the region is 668 ± 120 Tg. Out of this, 69% is soil carbon (0-20 cm depth) and 31% is vegetation carbon including both in above and belowground biomass. Of this total ecosystem C, forests account for 83% of C (554.4 ± 117.6 Tg), grasslands for 15% C (100 ± 23.4 Tg), wetlands account for 1.6% C (10.8 ± 2.1 Tg) and the Cerrados account for 0.4% C (2.8 ± 0.7 Tg).

Table 2.1: Native vegetation in Campos Gerais region.

		Grassland	Forest	Cerrado	Wetlands	Total
Area (ha)		1.006.007	2.127.423	31.548	85.234	3.250.212
Carbon (Mg ha^{-1})	Soil (0-20 cm)	$94.9_{\pm23.3}$	$165.3_{\pm27.2}$	$61.6_{\pm21.5}$	$123.4_{\pm24.9}$	
	Aboveground biomass	$2.4_{\pm0.3}$	$89.0_{\pm48.0}$	$13.6_{\pm5.3}$	$1.9_{\pm0.7}$	
	Belowground biomass	$2.1_{\pm0.6}$	$6.3_{\pm4.5}$	$12.2_{\pm8.8}$	$1.7_{\pm0.6}$	
	Total	$99.4_{\pm23.3}$	$260.6_{\pm55.3}$	$87.4_{\pm23.8}$	$127.0_{\pm24.9}$	
Carbon (Tg)	Soil (0-20 cm)	$95.5_{\pm23.4}$	$351.7_{\pm57.9}$	$1.9_{\pm0.7}$	$10.5_{\pm2.1}$	$459.6_{\pm62.5}$
	Aboveground biomass	$2.4_{\pm0.3}$	$189.3_{\pm102.1}$	$0.4_{\pm0.2}$	$0.2_{\pm0.06}$	$192.3_{\pm102.1}$
	Belowground biomass	$2.1_{\pm0.6}$	$13.4_{\pm9.6}$	$0.4_{\pm0.3}$	$0.1_{\pm0.05}$	$16.0_{\pm9.6}$
	Total	$100.0_{\pm23.4}$	$554.4_{\pm117.6}$	$2.8_{\pm0.7}$	$10.8_{\pm2.1}$	$668.0_{\pm120.0}$

*The areas were obtained from ITCG, (2017).

*The carbon stocks were obtained from Hartman et al. (2014), Abdala et al. (1998), De Castro and Kauffman, (1998); Silver et al. (2000), Pillar et al. (2009), Watzlavick et al. (2012), Mello et al. (2014), Sa et al. (2014) and Gonçalves et al. (2017a).

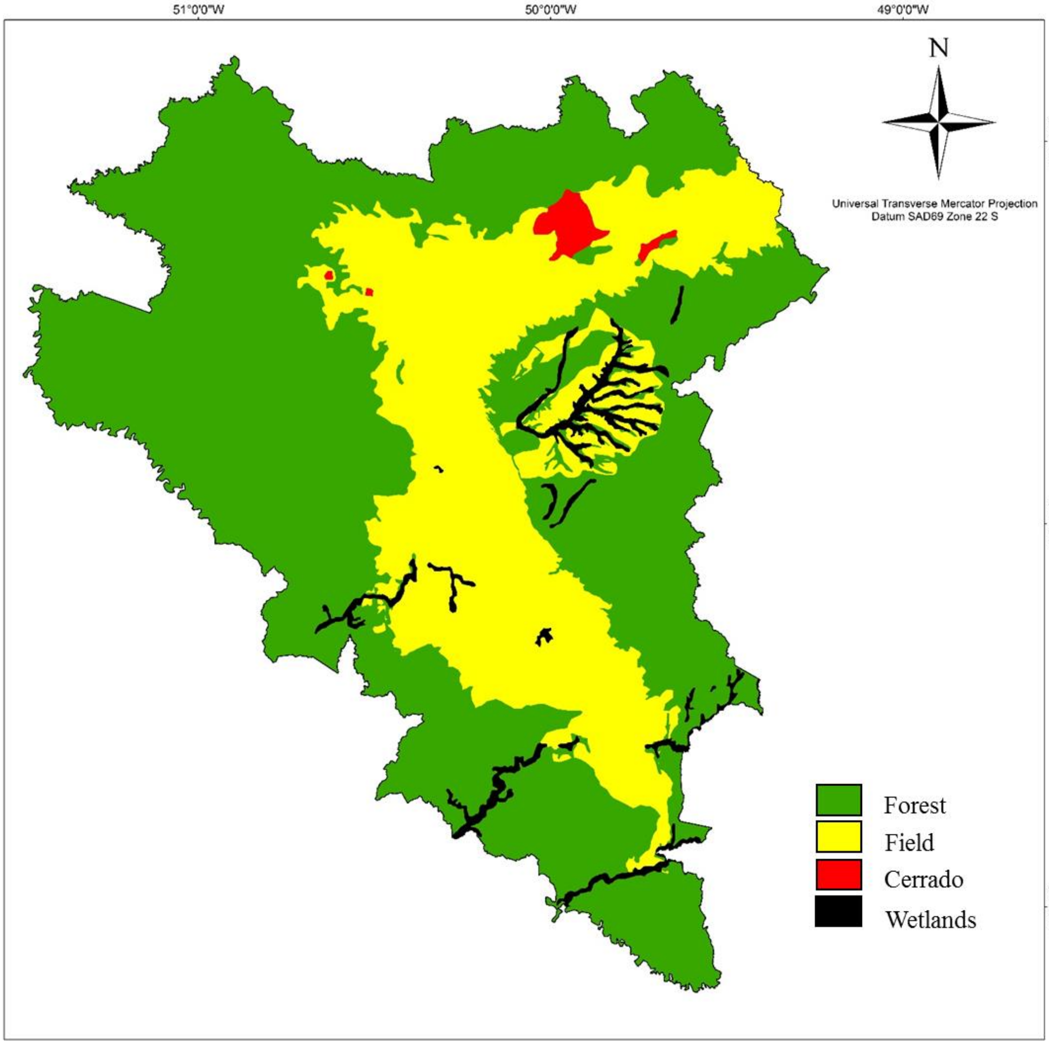

Figure 9: Native vegetation in Campos Gerais region.

2.3.2 Historic greenhouse gas emissions by land cover change in Campos Gerais region

The historical land cover change in the region began in 1930s with the conversion of grasslands, Cerrados and significant portion of forests and wetlands to pasture (Table 2.2). This caused the emissions from soil carbon oxidation, vegetation slash and burn and wetlands draining, decreasing the ecosystem C stock in the region. The native vegetation was reduced to 3.6% of the original land cover (116.119 ha) area. By 1970s the C in the native vegetation was reduced to 4.4% (29.2 ± 0.6 Tg) of the original and 8.5% of the new total carbon stocks, calculated summing the new C stocks of each land use system (Table 2.2), 340.7 Tg.

Table 2.2: Historical land use change in Campos Gerais region.

Year		Carbon stock (Mg ha^{-1})				
	Land use	NV		Economic activities		
		Forest	Wetlands	Pasture		
	Area (ha)	107.809	8.310	3.134.093		
1930 - 1969	Soil (0-20 cm)	$165.3_{\pm 27.2}$	$123.4_{\pm 24.9}$	$94.9_{\pm 23.3}$		
1930 - 1969	Aboveground biomass	$89.0_{\pm 48.0}$	$1.9_{\pm 0.7}$	$2.4_{\pm 0.3}$		
1930 - 1969	Belowground biomass	$6.3_{\pm 4.5}$	$1.7_{\pm 0.6}$	$2.1_{\pm 0.6}$		
1930 - 1969	Total	$260.6_{\pm 55.3}$	$127.0_{\pm 24.9}$	$99.4_{\pm 23.3}$		
	Total carbon (Tg)	$28.1_{\pm 6.0}$	$1.1_{\pm 0.2}$	$311.5_{\pm 73.0}$		
	Land use	Forest	Wetlands	Pasture	Planted forests	Agriculture
	Area (ha)	107.809	8.310	622.915	583.032	1.928.146
1970	Soil (0-20 cm)	$165.3_{\pm 27.2}$	$123.4_{\pm 24.9}$	$94.9_{\pm 23.3}$	$94.9_{\pm 23.3}$	$64.5_{\pm 23.3}$
1970	Aboveground biomass	$89.0_{\pm 48.0}$	$1.9_{\pm 0.7}$	$2.4_{\pm 0.3}$	-	$2.6_{\pm 0.35}$
1970	Belowground biomass	$6.3_{\pm 4.5}$	$1.7_{\pm 0.6}$	$2.1_{\pm 0.6}$	-	$1.0_{\pm 0.1}$
1970	Total	$260.6_{\pm 55.3}$	$127.0_{\pm 24.9}$	$99.4_{\pm 23.3}$	$94.9_{\pm 23.3}$	$68.2_{\pm 23.3}$
	Total carbon (Tg)	$28.1_{\pm 6.0}$	$1.1_{\pm 0.2}$	$61.9_{\pm 14.5}$	$55.3_{\pm 13.6}$	$131.4_{\pm 44.9}$
1971 - 1984	Soil (0-20 cm)	$165.3_{\pm 27.2}$	$123.4_{\pm 24.9}$	$94.9_{\pm 23.3}$	$117.9_{\pm 23.3}$	$40.5_{\pm 23.3}$
1971 - 1984	Aboveground biomass	$89.0_{\pm 48.0}$	$1.9_{\pm 0.7}$	$2.4_{\pm 0.3}$	$42.62_{\pm 6.0}$[£]	$2.6_{\pm 0.35}$
1971 - 1984	Belowground biomass	$6.3_{\pm 4.5}$	$1.7_{\pm 0.6}$	$2.1_{\pm 0.6}$	-	$1.0_{\pm 0.1}$
1971 - 1984	Total	$260.6_{\pm 55.3}$	$127.0_{\pm 24.9}$	$99.4_{\pm 23.3}$	$160.5_{\pm 23.8}$	$44.2_{\pm 23.3}$
	Total carbon (Tg)	$28.1_{\pm 6.0}$	$1.1_{\pm 0.2}$	$61.9_{\pm 14.5}$	$93.6_{\pm 13.9}$	$85.2_{\pm 44.9}$
1985 - 2017	Soil (0-20 cm)	$165.3_{\pm 27.2}$	$123.4_{\pm 24.9}$	$94.9_{\pm 23.3}$	$140.9_{\pm 23.3}$	$56.3_{\pm 23.3}$
1985 - 2017	Aboveground biomass	$89.0_{\pm 48.0}$	$1.9_{\pm 0.7}$	$2.4_{\pm 0.3}$	$42.62_{\pm 6.0}$[£]	$2.6_{\pm 0.35}$
1985 - 2017	Belowground biomass	$6.3_{\pm 4.5}$	$1.7_{\pm 0.6}$	$2.1_{\pm 0.6}$	-	$1.0_{\pm 0.1}$
1985 - 2017	Total	$260.6_{\pm 55.3}$	$127.0_{\pm 24.9}$	$99.4_{\pm 23.3}$	$183.5_{\pm 23.8}$	$60.0_{\pm 23.3}$
	Total carbon (Tg)	$28.1_{\pm 6.0}$	$1.1_{\pm 0.2}$	$61.9_{\pm 14.5}$	$107.0_{\pm 13.9}$	$115.6_{\pm 44.9}$

[£] Count for aboveground and belowground biomass.

After 1970s, part of the land converted to pasture was reconverted to planted forests and agriculture. About 18% (583 ha) was converted to planted forests, 59% (1.9 million ha) to agriculture and 19% (0.6 million ha) remained as pasture land. The land area under native vegetation, forests and wetlands, remained the same as of 1930s and did not changed any more. The increase in agricultural land area reduced the total amount of C in the region to 278 Tg, 63 Tg less than in late 1960s. The pasture accounted for 22% (61.9 ± 14.5 Tg), planted forests accounted for 20% (55.3 ± 13.6 Tg) and agriculture accounted for 47% (131.4 ± 44.9 Tg) of the new carbon stocks. The remaining native vegetation accounted for the other 10% (29.2 ± 0.6 Tg) C.

Between 1970 and 1984, the soil carbon stocks increased in planted forest lands from 95 to 118 Mg ha^{-1} due to the high C input trough leaves and branches. On the other hand, SOC in agriculture land decreased from 64.5 to 40.5 Mg ha^{-1} due to the soil tillage (Table 2.2). The C stocks in the vegetation of planted *Pinus sp. L.* and *Eucalyptus sp. L'Her* forests contributed to higher total C stocks, 270 Tg, similar to 1970. The highest ecosystem C stocks were observed in planted forests, 34.7% (93.6 ± 13.9 Tg), followed by agriculture, 31.6% (85.2 ± 44.9 Tg), pasture, 22.9% (61.9 ± 14.5 Tg) and native vegetation, 10.8% (29.2 ± 0.6 Tg).

During 1985s, the conversion of agriculture land cultivated with soil tillage to no-till system intensified, and by 2017, soil C stocks of both forest and agriculture lands increased. The agriculture accounted for 36.9% (115.6 ± 44.9 Tg), planted forests for 34.1% (107 ± 13.9 Tg), pastures for 19.7% (61.9 ± 14.5 Tg) and native vegetation for 9.3% (29.2 ± 0.6 Tg) of the total carbon stocks. The new soil C stocks become approximately equal to those of late 1960s (340.7 Tg), due to enhanced C sequestration in forest plantation and no-till cropping systems. The croplands contributed more to C stocks in absolute values. However, when the carbon stocks are measured in relative values (Mg ha^{-1}), the order is native vegetation (250.5 Mg ha^{-1}) > planted forests (183.5 Mg ha^{-1}) > pastures (99.4 Mg ha^{-1}) > croplands (60 Mg ha^{-1}).

The historic greenhouse gas emissions from LULUC was 456.1 Tg (Figure 2.4, 2.5), of which 94.5% was from land use change (436.4 ± 44.5 Tg), 5% from livestock (17.8 Tg), 0.4% from farm activities (1.4 Tg) and 0.1% from planted forests management (0.5 Tg). GHG emissions from LULUC was 12 times higher than the historical emissions from fossil fuel combustion (37.7 Tg), making the total emissions from the study region to be 493.8 Tg. The planted forest promoted C sequestration, 51.7 ± 23.9 Tg in 0.6 Mha land area in 47 years (1.8

Tg Mha^{-1} year^{-1}) and no-till system sequestered 30.4 ± 23.9 Tg in 1.9 Mha land area in 32 years (0.5 Tg Mha^{-1} year^{-1}). The waste recycling mitigated 1.5 Tg C year^{-1}, a total of 83.6 Tg C mitigated since 1970. Before 1930 the region emitted just 0.04 Tg C, however it was net source of GHG during 1930 to 1970, emitting 327.9 Tg C (8.2 Tg C year^{-1}) mainly driven by LULUC emissions. During 1970 to 1985 the GHG emissions decreased to 64.5 Tg (4.29 Tg C year^{-1}). In this period, soil tillage was the main source of GHG emissions. Finally, during 1985 to 2017 the region emitted 42.03 Tg C (1.31 Tg C year^{-1}). However, during this period the main contributor of GHG emission was fossil fuels (33.9 Tg or 1.06 Tg C year^{-1}). Planted forests and no-till contributed to keep LULUC emission close to neutral (8.1 Tg C at the rate of 0.2 Tg C year^{-1}).

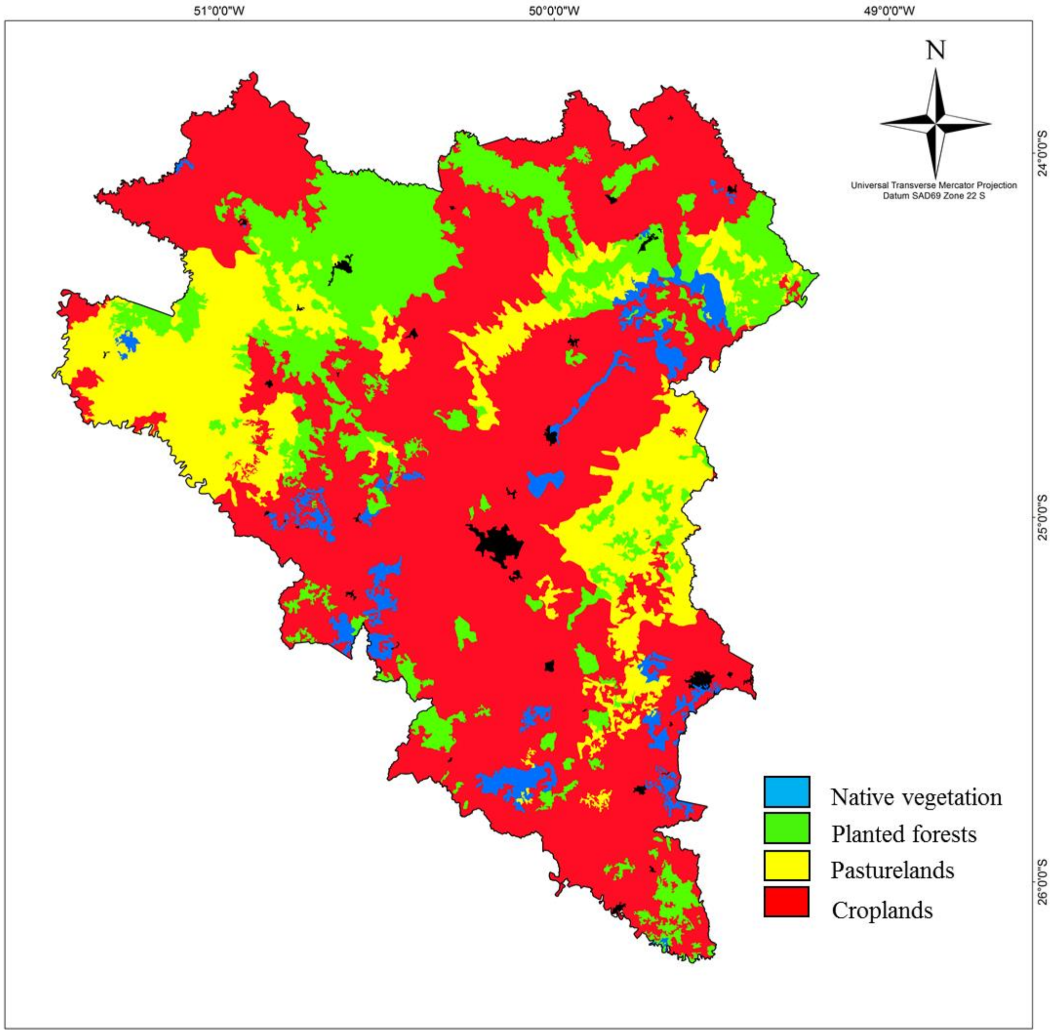

Figure 10: Land use in Campos Gerais region.

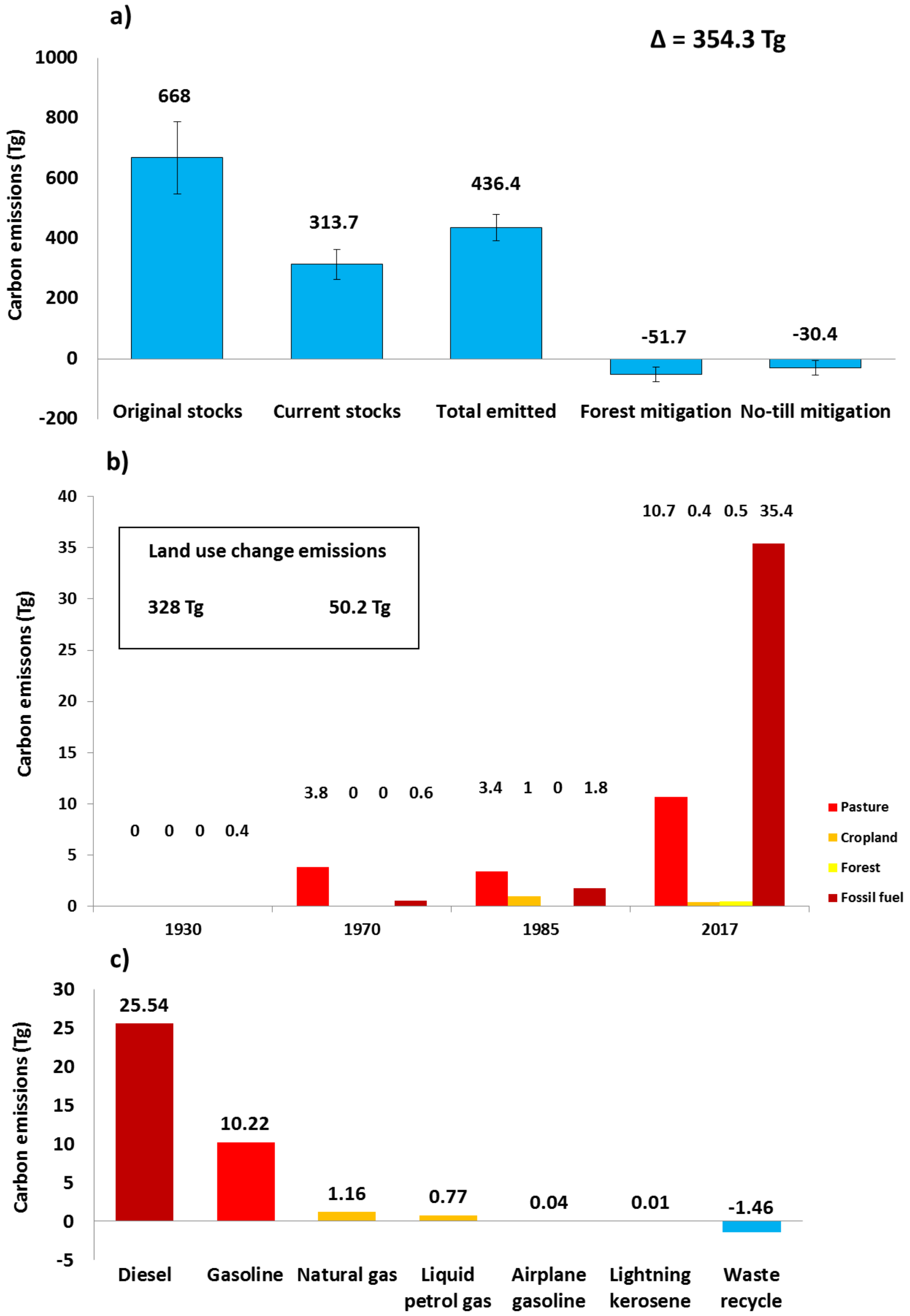

Figure 11: Historic greenhouse gases emissions: a) Ecosystem carbon stocks, emission from land use change and mitigation from LULUC sector; b) Historic emissions from land use and fossil fuel; c) Emissions from fossil fuel sector and waste recycle.

2.3.3 Current greenhouse gas emissions in Campos Gerais region

The annual GHG emission in Campos Gerais region is estimated to be 12.7 Tg CO_2 year^{-1} and the C savings by waste recycling is estimated to be 648 Gg CO_2 year^{-1} (5% of the total). Thus, the total annual GHG emissions are 12 Gg CO_2 year^{-1}, equivalent to 3.3 Gg C year^{-1} (Figure 2.6). Of the total GHG emitted (not counting the C saving by waste recycle), 12% is emitted from LULUC (1.5 Gg CO_2 year^{-1}). Livestock emission accounts for 97% of this total (1.4 Gg CO_2 year^{-1}). The other 88% (11.2 Gg CO_2 year^{-1}) is emitted from fossil fuels, with vehicle emissions (diesel and gasoline) accounting for 94% (10.6 Gg CO_2 year^{-1}) and natural gas vehicle (also used as a source of energy in the region) accounting for 5% (519 Gg CO_2 year^{-1}) of the emissions. This pattern is in contrast with the historical (1930 to 1970) GHG emission trend, in which LULUC had the biggest contribution to GHG emissions.

2.3.4 The role of conservation agriculture to mitigate greenhouse gas emissions and carbon offset

The potential of conservation agriculture for GHG mitigation in Campos Gerais region was studied by simulating the adoption of best management practices during next 100 years in the croplands of the region. With the adoption of the system in 2017, in 2067, the cropland SOC and total C stocks will be 22 and 10% higher compared to no adoption. By 2117, the agriculture SOC stocks will be 34% and the total C stocks will be 13% higher compared to no adoption, an increase of 41.9 Tg C (Figure 2.7, Table 2.3).

Moreover, the proposed system can mitigate 42 Tg of carbon until 2117. This is equivalent to 11% of the region C debit (historically emitted) from LULUC (Figure 2.5). Also, this magnitude of C sequestration is sufficient to mitigate 13 years of the regional emission (330 Tg in 100 years) or 105 years of agriculture forestry and other land use (AFOLU) emissions (40 Tg in 100 years) assuming no more LUC in the region (Figure 2.6).

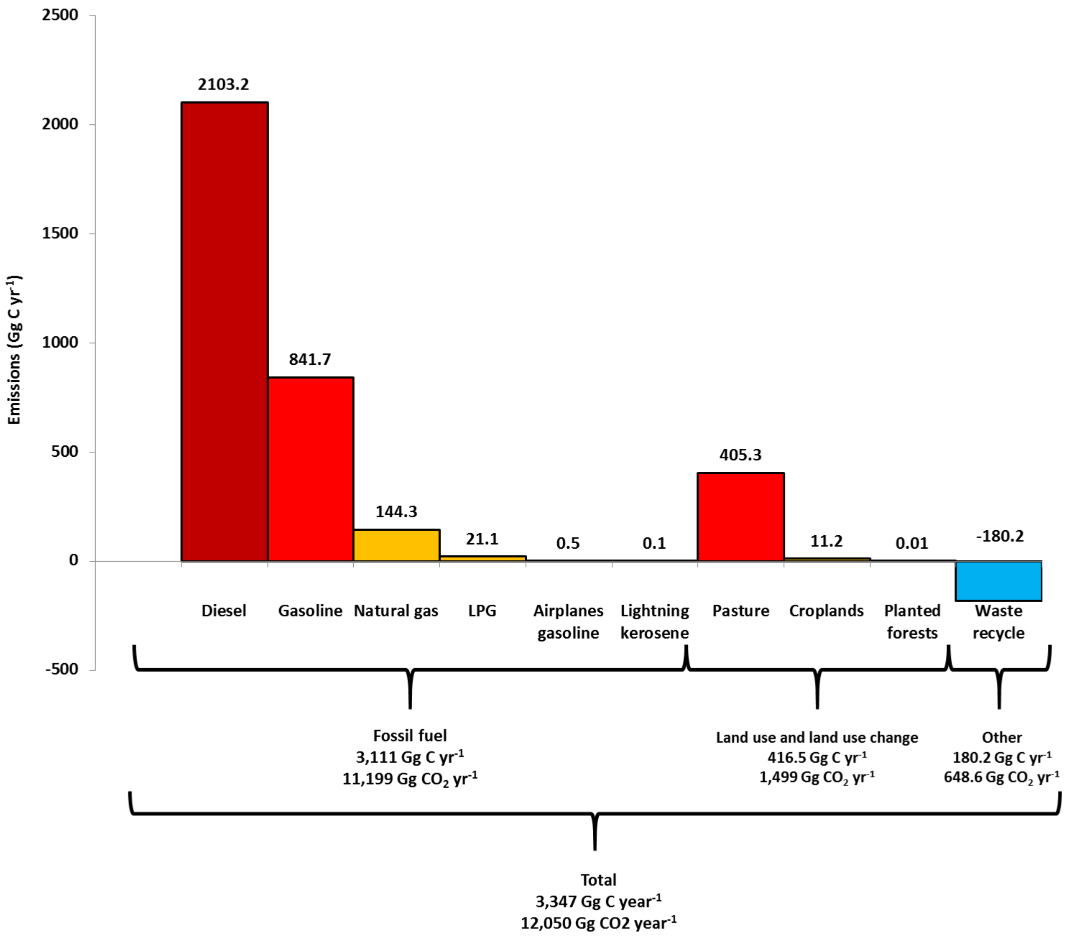

Figure 12: Annual greenhouse gases emissions in Campos Gerais region.

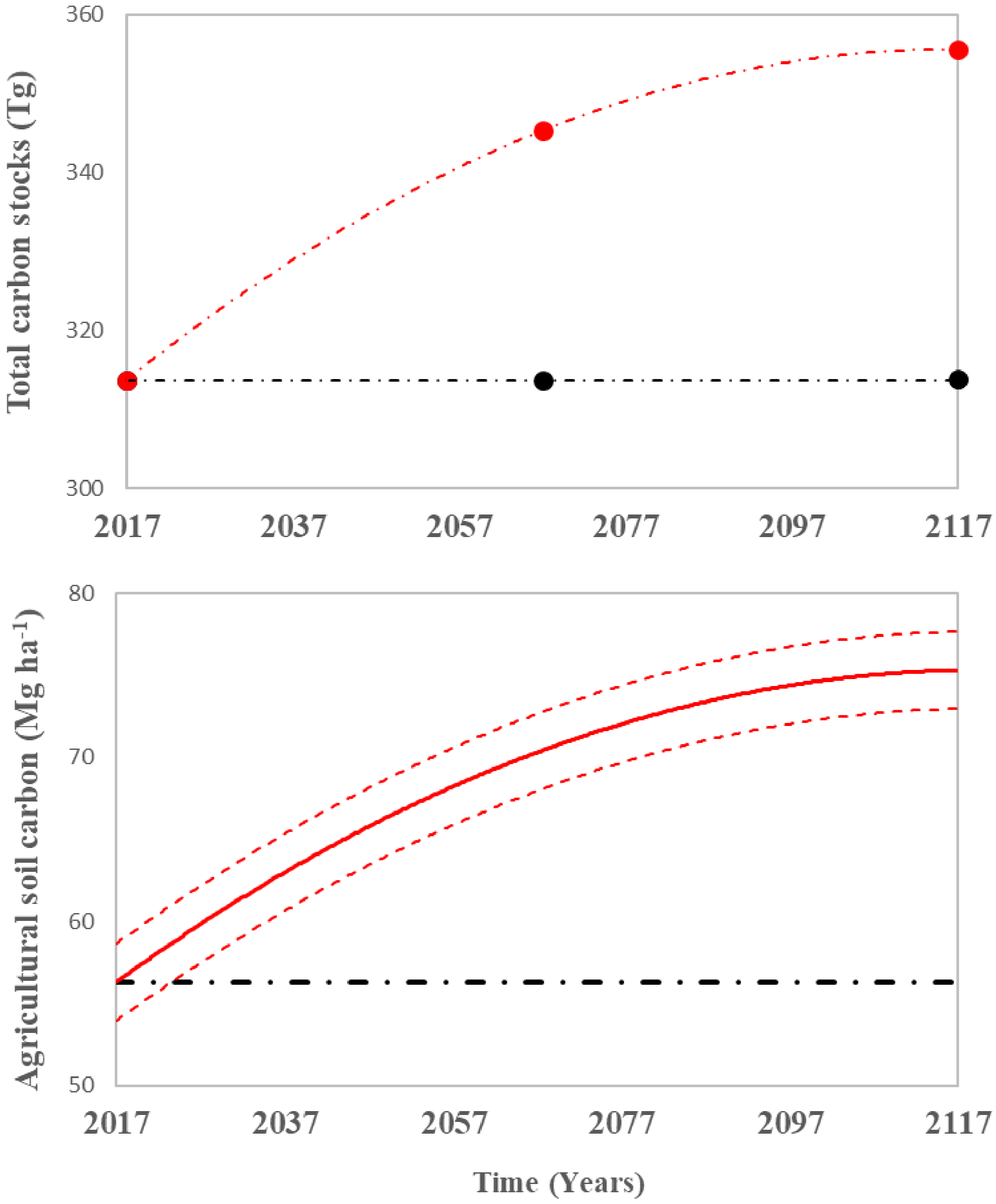

Figure 13: Future agriculture soil carbon stocks and total carbon stocks in Campos Gerais region considering the adoption of high quality no-till system.
* The black line refers to no adoption of high quality no-till, and the red refers to adoption in 2017. The dashed lines refer to 95% confidence intervals for the predicted values.

Table 2.3: Future scenarios with high quality no-till system adoption in Campos Gerais region.

Year	Carbon (Mg ha^{-1})	Native vegetation		Economic activities		
		Forest	Wetlands	Pasture	Planted forests	Agriculture
	Area (ha)	107.809	8.310	622.915	583.032	1.928.146
2017	Soil (0-20 cm)	$165.3_{\pm27.2}$	$123.4_{\pm24.9}$	$94.9_{\pm23.3}$	$140.9_{\pm23.3}$	$56.3_{\pm23.3}^{\S}$
2017	Aboveground biomass	$89.0_{\pm48.0}$	$1.9_{\pm0.7}$	$2.4_{\pm0.3}$	$42.62_{\pm6.0}^{\pounds}$	$2.6_{\pm0.35}$
2017	Belowground biomass	$6.3_{\pm4.5}$	$1.7_{\pm0.6}$	$2.1_{\pm0.6}$	-	$1.0_{\pm0.1}$
2017	Total	$260.6_{\pm55.3}$	$127.0_{\pm24.9}$	$99.4_{\pm23.3}$	$183.5_{\pm23.8}$	$60.0_{\pm23.3}$
	Total carbon (Tg)	$28.1_{\pm6.0}$	$1.1_{\pm0.2}$	$61.9_{\pm14.5}$	$107.0_{\pm13.9}$	$115.6\ _{\pm44.9}$
2018 - 2067	Soil (0-20 cm)	$165.3_{\pm27.2}$	$123.4_{\pm24.9}$	$94.9_{\pm23.3}$	$140.9_{\pm23.3}$	$70.3_{\pm26.1}\ ^{\pm2.3\text{€}}$
2018 - 2067	Aboveground biomass	$89.0_{\pm48.0}$	$1.9_{\pm0.7}$	$2.4_{\pm0.3}$	$42.62_{\pm6.0}^{\pounds}$	$4.5_{\pm0.6}$
2018 - 2067	Belowground biomass	$6.3_{\pm4.5}$	$1.7_{\pm0.6}$	$2.1_{\pm0.6}$	-	$1.8_{\pm0.3}$
2018 - 2067	Total	$260.6_{\pm55.3}$	$127.0_{\pm24.9}$	$99.4_{\pm23.3}$	$183.5_{\pm23.8}$	$76.7_{\pm26.1}$
	Total carbon (Tg)	$28.1_{\pm6.0}$	$1.1_{\pm0.2}$	$61.9_{\pm14.5}$	$107.0_{\pm13.9}$	$147.9_{\pm50.3}$
2068 - 2117	Soil (0-20 cm)	$165.3_{\pm27.2}$	$123.4_{\pm24.9}$	$94.9_{\pm23.3}$	$140.9_{\pm23.3}$	$75.3_{\pm26.1}\ ^{\pm2.3}$
2068 - 2117	Aboveground biomass	$89.0_{\pm48.0}$	$1.9_{\pm0.7}$	$2.4_{\pm0.3}$	$42.62_{\pm6.0}^{\pounds}$	$4.5_{\pm0.6}$
2068 - 2117	Belowground biomass	$6.3_{\pm4.5}$	$1.7_{\pm0.6}$	$2.1_{\pm0.6}$	-	$1.8_{\pm0.3}$
2068 - 2117	Total	$260.6_{\pm55.3}$	$127.0_{\pm24.9}$	$99.4_{\pm23.3}$	$183.5_{\pm23.8}$	$81.7_{\pm26.1}$
	Total carbon (Tg)	$28.1_{\pm6.0}$	$1.1_{\pm0.2}$	$61.9_{\pm14.5}$	$107.0_{\pm13.9}$	$157.5_{\pm50.3}$

2.4 DISCUSSION

2.4.1 Native vegetation, land use change and historical emissions

Patterns of natural vegetation in the Campos Gerais region described in this study (Table 2.1, Figure 2.3) are consistent with the results of previous studies (MELO et al., 2007; ROCHA and WEIRICH NETO, 2010). Rocha and Weirich Neto (2010) reported that the native vegetation was dominated by grasslands, forests, a-mix of these two land covers and wetlands in this region. These studies also reported that about 70% of the land area was converted to cultivated land, and the native vegetation on remaining areas were basically permanent preservation areas protected by law along the rivers borders (FLORESTAL, 2016). The current small portion of native vegetation occupying 3.6% (Table 2.2, Figure 2.4) of the land area is consistent with these results. The total emissions in Campos Gerais region are estimated to be 412.2 Tg C (Figure 2.5). Out of this, LUC accounted for 356.5 Tg C and the biggest LUC occurred during 1930s emitted 297.3 Tg of C (Table 2.1, 2.2).

Conversion of pasture to agriculture land in 1970s emitted 62.9 Tg of C (Table 2.2, Figure 2.4). Other studies from the same region (SÁ et al., 2015; SÁ et al., 2014), reported reduction in SOC stocks by 33% and 27% in the 0-20 cm layer due to conversion of native prairies to agriculture land after 23 years. Villarino et al. (2014) performed an IPCC tier 2 (PACHAURI et al., 2014) agriculture GHG emissions inventory and reported that the conversion of grassland to cropland reduced the SOC stocks by 25% (0.75 ± 0.01) in the Argentinian Pampa region. Mello et al. (2014) reported that SOC stocks reduced by 10% (5.7 ± 2.2 Mg ha^{-1}) due to conversion of pasture land to sugarcane cultivation despite the higher biomass production potential of sugarcane.

In 1985, it is possible to observe the potential of forests to sequester C and mitigate GHG emissions. It offset the emissions from soil tillage in agriculture land, keeping the C stocks about 269.9 Tg (Table 2.2, Figure 2.4). The negative effects of soil tillage are well documented (LAL, 2004). Soil tillage reduced SOC stocks by 26.7% and 16% compared to native vegetation and no-till in Campos Gerais (SÁ et al., 2001; TIVET et al., 2013). On the other hand, several studies reported the power of planted forests as a C sink. The forests store 75% of the world biomass and currently are a sink of 0.7 Pg C year^{-1} (FEDERICI et al., 2015; KÖHL et al., 2015; KOLIS et al., 2017). Davis et al. (2012) estimated that eastern US forests could mitigate 63 Tg C year^{-1} from fossil fuel emissions if used for ethanol production and sink 8 Tg C year^{-1}. Sá et al. (2017) estimated that planted forests could sequester 1.06 Pg of C between 2016 and 2050 in South American continent. In addition, although quite modest, the carbon credits market considers forestry as an activity for GHG mitigation (PAUL et al., 2013; RUDDELL et al., 2006; CHICAGO CLIMATE EXCHANGE, 2017). However, the conversion of forest areas for croplands (JOSHUA et al., 2017) are considered a potential source of GHG emissions. This highlights the importance of agriculture intensification to mitigate GHG emissions.

Between 1985 and 2017, no-till system and planted forests sequestered 43.8 Tg C (Table 2.2), out of which 30.4 Tg C was due to no-till. Both no-till and forestry mitigated 8.5% of GHG total historical emissions. No-till is widely reported as an important tool to sequester C and mitigate GHG emissions (LAL, 2016; MINASNY et al., 2017). In no-till system, for the first 20 years C sequestration rates in sub-tropical region ranged between 0.2 and 0.9 Mg ha year^{-1} in the 0-20 cm soil layer (BAYER et al., 2006; FERREIRA et al., 2012; ZANATTA et al., 2007). However, the magnitude of C sequestered can be up to 1.42 Mg ha year^{-1} considering 0-100 cm soil layer (DIECKOW et al., 2006). In addition, many studies relate other benefits of no-till including prevention of soil erosion and increase of crop yields for sub-tropical agro ecosystems (GONÇALVES et al., 2017a; LAL, 2001).

The described pathway of GHG emissions is expected to occur in other sub-tropical regions (e.g Africa and Southeast Asia) to meet the global need for food production (FOLEY et al., 2011). Therefore, special attention is needed for conservation practices to reduce the impacts of LUC.

2.4.2 Current emissions

As Campos Gerais does not have cement production facilities, the main source of GHG emissions in the region is fossil fuel combustion, 11.2 Gg CO_2 year^{-1} (Figure 2.6). Hydropower, which is considered as a clean and renewable source (PACHAURI et al., 2014), is a major source of energy in the Campos Gerais region. Some recent studies demonstrated that GHG emissions, especially methane from dam's water reservoirs could be higher (DEEMER et al., 2016; SCHERER and PFISTER, 2016). However, more information is necessary to account for dam's GHG emissions in life cycle assessments. Some studies reported the acid wetlands from Paraná State to have small population of methane producing bacteria and archaea. Suggesting its methane emissions can be small (ETTO et al., 2014; ETTO et al., 2012). Other sources of energy production in the region include solar and wind energy.

Transportation accounted for 95% of fossil fuel emissions in Campos Gerais region. Out of which, diesel accounted for 68% and gasoline plus natural gas accounted for 27%

(Figure 2.6). These values suggest that adoption of electrical vehicles can lead to massive reduction of GHG emissions. Wu and Zhang (2017) proposed the use of electrical vehicles to mitigate GHG emissions and increase oil security in developing countries that have hydropower as primary energy source. In countries with high GHG emission from energy generation (e.g. China and India), adoption of electrical vehicles can help to mitigate GHG emissions only if decarbonisation of energy sector is accomplished (HOFMANN et al., 2016; ONN et al., 2017). Thomas (2012) reported that the substitution of all vehicles by electric could mitigate 25% of US GHG emissions. However, this amount can increase up to 44% GHG mitigation through the adoption of hydrogen vehicles not dependent from energy production. Of the top energy consumers (more than 100 Tg oil equivalent), only Brazil (73.5%) and Canada (67.2%) have more than 60% of energy production coming from clean sources (GLOBAL ENERGY STATISTICAL YEARBOOK, 2016). Which indicate that the substitution of oil products in transport energy can have great impact on these countries emissions.

The contribution of waste recycling in mitigating GHG emissions is still quite modest, but enough to mitigate annual emissions from LULUC sector (Figure 2.6). Waste recycling has been growing in Campos Gerais region because of public programs that provide incentives for this sector (CURITIBA, 2017; PONTA GROSSA, 2017). Currently, about 9% of the region's waste is recycled, this value is still far less in comparison to the average of the top ten recycling countries in the world (49%) which indicate scalability potential of this technology (BALDÉ, 2015).

The historical pattern of the Campos Gerais region's emission was similar to Brazilian emissions in 2005 with 58% emissions from land use change and 20% from agriculture and differ from the current patterns were energy is responsible for 37% of emissions and land use change reduced to 15% (BRAZIL, 2014). The CO_2 emission from soil management was not considered in the national scale inventory because of the high adoption rates of no-till system in Brazil (CONAB, 2012). However, historically it can be a significant source of CO_2 emission. In addition, accounting of no-till C sequestration and the reduction of deforestation by agriculture intensification can be fundamental for Brazil to meet its goals to reduce GHG emission by 43% between 2015 and 2030 (ESCOBAR, 2015).

In contrast, the current pattern of the region emission is similar to European countries were the energy plus industrial processes emissions represents about 83% of total emissions and agriculture plus waste represent the others 17% (SU et al., 2016). This shows that regions that are currently emitting CO_2 from LULUC sector can change to fossil fuel in the future.

Annual LULUC emissions are ten times lower (13.4%, 1.5 Gg CO_2 year^{-1}) than the fossil fuel emissions (Figure 2.6). Agriculture and planted forests emissions are low, accounting for just 2.7% or 0.01 Tg C year^{-1} (Figure 2.6), and GHG mitigation by soil and trees C sequestration was 1.37 Tg C year^{-1} between 1985 and 2017 (Table 2.2). In this way, livestock remains the major source of GHG emissions in Campos Gerais region. This pattern is consistent with the results of Smith et al. (2014) who reported that after LUC (40% or 1.08 Pg Ceq. year^{-1}) livestock emissions (33% or 0.89 Pg Ceq. Year^{-1}) is the second biggest source of GHG from AFOLU sector. It is especially important in Brazil, India, China and US that have more than 600 million cattle heads or 40% of the world flock (FAO, 2015). However, the intensification of livestock production systems may lead to GHG mitigation since it can reduce deforestation, activity that is the major source of GHG emission (Table 2.2) especially in Amazon region (DA SILVA et al., 2017).

2.4.3 Future scenarios and carbon offset

Our results suggest that adoption of best management practices can mitigate 42 Tg C until 2117 (Table 2.3, Figure 2.7) making AFOLU sector a net C sink. This indicates that conservation agriculture is a powerful tool to mitigate GHG emissions. The C sequestration rate achieved with the adoption of the system in 2017 for the first 50 years is 0.26 Mg ha^{-1} year^{-1} (Table 2.3). This value match with the proposed rate of C sequestration in the four per mille (0.4%, 0.22 Mg ha^{-1} year^{-1}) concept (LAL, 2016; MINASNY et al., 2017) for the first 20 years. It is important to mention that the croplands of Campos Gerais region has initial C stock of 56.3 Mg C ha^{-1} and the Paiquerê farm has been under best management practices since last 32 years (Table 2.3). We expect higher C sequestration rates for the croplands that will adopt the system in this region. The system potential can be even higher up to 100 cm depth. In other study using Paiquerê farm database, the authors found that the 0-20 cm depth have just 56% of SOC content (GONÇALVES et al. 2015a), in this way the total SOC stocks can be up to 100.5, 125.5, 134.5 Mg ha^{-1}, wich is equivalent to 193.8, 242 and 259. 3 Tg, in 2017, 2067 and 2117 for the entire region respectively.

Some studies reported no difference in crop yields under different soil tillage systems (VOGELER et al., 2009) or even lower crop yields in no-till system (OGLE et al., 2012; PITTELKOW et al., 2015) specially in temperate climates. However, studies from sub-tropical and tropical climates showed higher yields between 20 and 70% in no-till systems in comparison to soil tillage management (BHARDWAJ et al., 2011; SÁ et al., 2015; FRANCHINI et al., 2012; KUHN et al., 2016). Thus, we argue that no-till can help to close yield gaps, enhance food production and mitigate GHG emissions in sub-tropical and tropical regions (FOLEY et al., 2011; LAL, 2004).

Despite the stated benefits, agricultural systems also have adoption constraints as suggested by Vandenbygaart (2016). The author reported that less than 10% of American farmers practice continuous no-till and N_2O emission could negatively balance C sequestration. Some studies also reported that C sequestration in no-till systems is limited to upper soil layers (POWLSON et al., 2014). Our study in a production farm managed under continuous no-till can reduce these constraints. Del Grosso et al. (2005) reported that C emission from no-till in US were in average 0.29 Mg C ha^{-1} year^{-1} compared to 0.43 Mg C ha^{-1} year^{-1} for soil tillage-based system. Post et al. (2012) related that no-till emissions of N_2O and CH_4 are dependent of various biotic and abiotic factors, even so no-till adoption can mitigate up to 1.22 Mg CO_2 ha^{-1} year^{-1} in US soils. In addition, some recent studies reported C increase in subsoil layers of no-till systems (GONÇALVES et al., 2015; RUMPEL and KÖGEL-KNABNER, 2011; SÁ et al., 2014). These authors attribute the C increase in subsoil layers to high-developed root systems.

The adoption of best management practices by farmers in large areas will require a coordinated effort with policymakers as described by Minasny et al. (2017). It will depend on farmers knowledge and provision of government subsidies for cost recovery in early years of adoption. The current adoption of no-till systems by 99% farmers in Campos Gerais region, although in different quality levels, can reduce the adoption costs (BRÜGGEMAN, 2013). In addition, the profitability of no-till system with government incentives for GHG mitigation can help to promote the adoption in other potential regions. Lal (2004) proposed that global soils have the potential to sequester 0.4 to 1.2 Pg C year^{-1}, 5 to 15% global fossil fuel emissions. Sá et al. (2017) proposed that no-till system could sequester 2.01 Pg C between 2016 and 2050. Though the adoption of best management practices at large scales is still uncertain and far from be a panacea, the system presents a high potential to increase and sustain crop yields and mitigate GHG emissions in sub-tropical and tropical croplands.

2.4.4 Ecosystem services upon conservation agriculture

As described in many studies, the payment for C sequestration can lead to the development of mitigation activities in many sectors, including agriculture. Mean carbon prices of 10 USD Mg CO_2 eq. (KUMAR and NAIR, 2011) would imply 18.2 USD ha^{-1} year^{-1} for the first and 5.2 USD ha^{-1} year^{-1} for the final 50 years, resulting in 900 million USD for the first and 270 million USD for the second 50 years (1.17 billion or 12 million year^{-1}) for the entire region. The main gaps delaying the development of such markets are limitation of economic benefits, the development of monitoring and regulation systems and in many cases a negative public opinion (LAURENT et al., 2017). Especially for the case of SOC, uncertainties related to it mean turnover time and soils potential to sequester C, are described as main gaps (GREN and CARLSSON, 2013). Account for SOC is interesting because the consideration of many pools can reduce the mitigation risk and costs (ELLISON et al., 2014). Elofsson and Gren (2018) reported that account for SOC pool can reduce European carbon taxes by 33 to 50%. In addition to C price, environmental services have to be considered. Telles et al. (2011) estimated an erosion cost in Paraná State of 242 million USD year^{-1} and Foster et al. (1987) reported that a reduction in 10% of soil erosion can reduce water treatment costs by 4%.

2.4.5 Study approach and uncertainty analysis

The capacity of soil C models (e.g. Century, DayCent, and Roth-C) to simulate long term SOC dynamics is limited to the current knowledge of: i) the rate of C accumulation in soils under different management systems, and ii) the soil's limited capacity to store C. The rate of C accumulation in soils varies depending upon initial C stocks, the type of management (e.g. no-till, minimum till and full soil tillage) and the time after the management adoption (MINASNY et al., 2017; ZANATTA et al., 2007). Zanatta et al. (2007) reported six different C accumulation rates for two systems (no-till and soil tillage) under three different crop rotation regimes. All the C accumulation rates decrease with time since the beginning of the experiment. Under more intensive rotations (Oat + Vetch/ Maize + Cowpea), SOC sequestration rate reduces from 1.0 to 0.6 Mg C ha^{-1} year^{-1} from the ninth to eighteenth year of adoption. Minasny et al. (2017) reported that soil C sequestration is lower in sites with high SOC content and the sequestration rate decreases with time after no-till adoption. In soils with low SOC stocks (<10 Mg C ha^{-1}), the sequestration rate was 0.2% per year, in comparison to 0.04% per year when SOC stocks were 80 Mg C ha^{-1}. The same way the sequestration rates decreased from 1.7 to 0.04% per year from zero to 50 years of no-till adoption.

Moreover, the soil's capacity to store C depends on mineralogical, physical, chemical and biological characteristics (SIX et al., 2002; STEWART et al., 2008). Briedis et al. (2016), working with sub-tropical Oxisols did not observe soil C saturation in a 30 months laboratory experiment even with an input of 24 Mg C ha^{-1} year^{-1}. This indicated that tropical and sub-tropical soil have a high capacity to store C. Gonçalves et al. (2017a) attributes the high capacity of sub-tropical soils to store C to the high content of Fe and Al oxides, however the soil aggregation process can help to explain it since its limit to store C is not reported. In a different approach, Century model predicts the SOC storage in ecosystems as a function of biomass input, resulting in a new equilibrium stage with changes in the original input (PARTON et al., 1988). Minasny et al. (2011, 2017) reported the same behavior in Java Island. They reported that the SOC sequestration rate increased from -0.6 to 0.4 Mg ha^{-1} year^{-1} following the sequence of high-intensity cropping to improved soil management in tropical ecosystems.

Despite improving knowledge of SOC dynamics, the effect of climatic change, particularly increase of atmospheric CO_2 and temperature on soil C stocks are still uncertain. The CO_2 fertilization effect on net primary production and the temperature increase on soil microbial activity, leading to higher CO_2 emission, create a complex scenario. Thus, the existence of a positive or negative feedback processes leading to SOC emission or sequestration is still one of the main knowledge gaps (ABEBE et al., 2016; O'LEARY et al., 2015).

Another source of uncertainty is the model structure (LUO et al., 2016; OGLE et al., 2010; OGLE et al., 2007; OGLE et al., 2006). Ogle et al. (2010) performed simulations for soil C stocks changes in the continental USA. They reported that 97.6% of the uncertainty in the result comes from model structure, and 2.4% from data inputs and scaling up. However, we found different sources of uncertainty in our study. We found data input as the biggest source of uncertainty and the model structure accounted for just 9% (Table 2.3, Figure 2.7). The total uncertainty in the SOC stocks varied according to land use category but ranged between 13% in planted forests to 36% in total LULUC emissions (Tables 2.2 and 2.3). Lal (2004) reported 50% uncertainties in estimating the C sequestration potential of world soils and Lugato et al. (2014) reported uncertainties ranging between 20 to 80% for European SOC stocks estimation.

In this study, the main limitation was the lack of data regarding historical land uses and number of vehicles in the region to estimate more accurate GHG emissions backward simulations can contribute to reduce this limitation. The limited number of studies that look for C stocks in soil and vegetation in sub-tropical regions also added some assumptions. These constraints were main contributors to the observed uncertainties. Despite these limitations, our study provides a robust GHG inventory accounting for past and current emissions, which describes the emission patterns as the Campos Gerais region developed. This tier 2 (PACHAURI et al., 2014) approach can be used as a model to generate GHG inventories and project different mitigation scenarios. In this way, it can contribute to drive public policies that aim to address food security and GHG emissions mitigation challenges.

2.5 CONCLUSIONS

Our results showed that until 1985 most of the region GHGs were emitted from LULUC. However, between 1985 and 2017 most GHG emissions were emitted from fossil fuel combustion. Forest plantations and currently practiced no-till system contributes to compensate for the emissions from agriculture, forestry and other land uses sector, making net emissions close to neutral (0.2 Tg C year^{-1}) in the last 30 years. The observed emission patterns highlight a large impact of LUC on total GHG emissions. In this way, conservation agriculture can play an important role in providing food and other resources for the growing population while avoiding new LUC.

Model simulation results showed that the adoption of best management practices at a regional scale can be an important tool to promote agriculture intensification and GHG mitigation. The proposed system can mitigate 26.6 and 42 Tg C in the next 50 and 100 years, respectively, 11% of the historical LULUC emissions. This technology can also mitigate 13 years of total emissions and 105 years of AFOLU emissions. This system demonstrates potential to turn the AFOLU sector from a source of CO_2 to a net sink. We note that the adoption of the proposed system will also provide sufficient time in the next 100 years for new technologies development that can help to further reduce the GHG emissions.

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CHAPTER 3 – CONSERVATION AGRICULTURE BASED ON DIVERSIFIED AND HIGH-PERFORMANCE PRODUCTION SYSTEM LEADS TO SOIL CARBON SEQUESTRATION IN SUB-TROPICAL ENVIRONMENTS

Abstract: Soils can be a source or sink of atmospheric CO_2, depending on the historic and existing land use and management. We hypothesized that the adoption of best management practices based on principles of conservation agriculture such as: a) eliminate soil disturbance, b) maintain permanent soil surface cover and adopt crop diversity with high biomass-C input, leads to restore soil organic carbon (SOC) stocks and contributes to reduce atmospheric CO_2 concentration. We used long term soil management database of a production farm that is under conservation agriculture for 30 years and agroecosystem models to study the potential of different management options to sequester carbon (C) in soils. Using Century and Roth-C models we simulated four sub-tropical soil management scenarios and studied C sequestration potential. Our results demonstrate that SOC continuously increased after best management practices adoption in 1985 until 2015, and currently SOC is in equilibrium. We found that an increase of 2.2 Mg ha^{-1} year^{-1} biomass-C input for 60 years resulted into increase of 12 Mg ha^{-1} SOC stocks. The same way, crop yields increased with time, and were more pronounced for maize compared to soybean and wheat. The scaling of results to similar climate and soil types indicated that best management practices has the potential to sequester 2.5±0.02 Pg C at 0-20 cm and 11.7±3 Pg C at 0-100 cm soil depth in 86 million ha area globally. This equilibrium SOC stocks are equivalent to 7 to 9% of the world SOC stocks in 6% of the world croplands and correspond to 11 years of global land use and land use change emissions, indicating that best management practices are a powerful tool to promote C sequestration in sub-tropical soils.

Key-words: Best management practices; sub-tropical agroecosystem; greenhouse gases mitigation; crop yield; Century model; Roth-C model

List of acronyms: C, Carbon; CEC, Carbon exchange capacity; GHG, Greenhouse gases; GIS, Geographic information system; IPCC, International panel on climate change; LULUC, Land use and land use change; N, Nitrogen; NT, No-till; US, United States of America; USDA, United states department of agriculture.

3.1 INTRODUCTION

Globally about 1.1±0.5 Pg C yr^{-1} is emitted through land use and land use change (LULUC). Of this total, 1.41±0.17 Pg C yr^{-1} is emitted in the tropics and the northern mid latitudes act as a sink of -0.28±0.21 Pg C yr^{-1}. The historical emissions by LULUC since the beginning of industrial era accounts for 227 ± 74.5 Pg C, 78 Pg C of which has been emitted through soil cultivation and 67 Pg C has been emitted through burning of natural vegetation (HOUGHTON, 2014; LAL, 2004; LE QUÉRÉ et al., 2015). New technologies such as conservation agriculture (LADHA et al., 2016; SÁ et al., 2017) have been developed to reduce greenhouse gas (GHG) emissions from land cultivation. Conservation agriculture shows a promise as it can be used to enhance C sequestration in soil and biomass and increase agricultural productivity (LAL, 2004; MINASNY et al., 2017). Lal (2004) reported that 0.4 to 0.8 Pg C yr^{-1} could be sequestered in the world croplands (1350 Mha) with the adoption of conservation agriculture practices. Del Grosso et al. (2005), reported that conversion from soil tillage system to no-till in US could mitigate 20% of agricultural emissions or 1.5% of total US GHG emissions. Post et al. (2012) reported that C sequestration in US croplands with no-till practices can be increased to 1.2 Mg CO_2 eq. ha^{-1} yr^{-1}, totaling 110 Tg CO_2 eq yr^{-1}. Recently, Sá et al. (2017) reported that the adoption of conservation agriculture in South America could mitigate 0.28 Pg C yr^{-1} for 35 years. These authors also estimated that no-till can mitigate ~ 6.4% of the world LULUC emissions and can serve as an important tool to reduce atmospheric CO_2 concentrations. Minasny et al. (2017) proposed a framework for the adoption of the SOC four per mille plan, discussed in the COP 21 United Nation sustainable innovation forum. This plan aims to increase the world soil C stocks by 0.04% per year for next 20 years, to mitigate GHG emissions.

Several studies explored C dynamics in conservative systems and supported these management options (DIEKOW et al., 2005; MISHRA et al., 2010; NADEU et al., 2015; SÁ et al., 2014). However, most of the management system experiments are relatively recent with less than 30 years of adoption (RASMUSSEN et al., 1998). In addition, the absence of production farming system under long-term conservative practices makes a technology development process difficult because of the constraints to adapt experimental plot results to production farms. Knowledge gaps about the improvement of crop production systems and understanding the GHG mitigation potential of conservation agriculture systems are described in the fifth assessment report of IPCC (PACHAURI et al., 2014), and has been receiving attention of the scientific community. Thus, we think that knowledge gaps associated with the crop yields improvement and its role in C sequestration in soils, is one of the main constraint to adapt experimental results at larger scales.

Some studies reported that the potential of conservation agriculture to sequester C in soils could be too low for meaningful mitigation of GHG emissions from agriculture (POWLSON et al., 2014; VANDENBYGAART, 2016). In addition, some studies reported lower crop yield under no-till systems compared to conventional or full tillage systems (OGLE et al., 2012; PITTELKOW et al., 2015). Thus, an important question need to be addressed: Despite some results from experimental plots, can we really develop best conservative systems? And what will be the impact of adopting it at global scale where it is suitable?

Thus, the objectives of this study were to: (i) study crop yield and SOC stock change using a 16 years database from a production farm that was under best management practices for last 30 years; (ii) simulate the historical (up to 2015) and future (up to 2075) SOC dynamics due to land use change based on four scenarios – a) existing farm biomass input (14.5 Mg ha^{-1} year^{-1}) or C input (6.5 Mg ha^{-1} year^{-1}); b) 15% increase of farm biomass input (16.7 Mg ha^{-1} year^{-1}) or C input (7.5 Mg ha^{-1} year^{-1}); c) 15% decrease of farm biomass (12.3 Mg ha^{-1} year^{-1}) or C input (5.5 Mg ha^{-1} year^{-1}) and, d) 30% decrease of farm biomass input (10.1 Mg ha^{-1} year^{-1}) or C input (4.5 Mg ha^{-1} year^{-1}) with Century and Roth-C agroecosystem models; (iii) Validate the simulations with the farm database; (iv) scale up the results to similar sub-tropical agroecosystems globally using geographic information systems (GIS).

3.2 MATERIAL AND METHODS

3.2.1 Study area

This study was conducted at Paiquerê Farm, located at 24° S 20’ 20” and 50° W 07’ 31” (Figure 3.1) near Piraí do Sul city at State of Paraná, Southern Brazil. The farm has a database (from 1997 to 2013) with detailed information on the climate, soil survey, fertilizer use, grain yield evolution and crop data being managed for more than 30 years under continuous best management practices. This farming system was chosen as it represents best management practices in the Campos Gerais region, where conservative practices follows three principles (no soil disturbance, continuous soil surface cover and diversity of crop rotation). It also includes the use of broad-graded terraces to control the runoff of rainwater. The crop rotation that comprises three successions, wheat (Triticum aestivium L.)/ soybean

(Glycine max L.), wheat/soybean for the second year and Oat (Avena sativa L.)/ Maize (Zea Mayz L.) result in a biomass input for wheat/soybean of 11.5 Mg ha^{-1} year^{-1} and for oat/maize system 20.5 Mg ha^{-1} year^{-1}, which provided the mean annual biomass input of 14.5 Mg ha^{-1} year^{-1} (GONÇALVES et al., 2017). In addition, the productivity of this farm (average of the last five years) is higher than the regional average. The productivity of maize is 10.5 Mg ha^{-1}, soybean is 4.0 Mg ha^{-1} and wheat is 3.6 Mg ha^{-1}, representing 26, 29 and 23% higher than those of the regional averages, respectively. This study site represents an example of a successful best management practices farming system and is ideal to explore the potential of it to sequester C in soils.

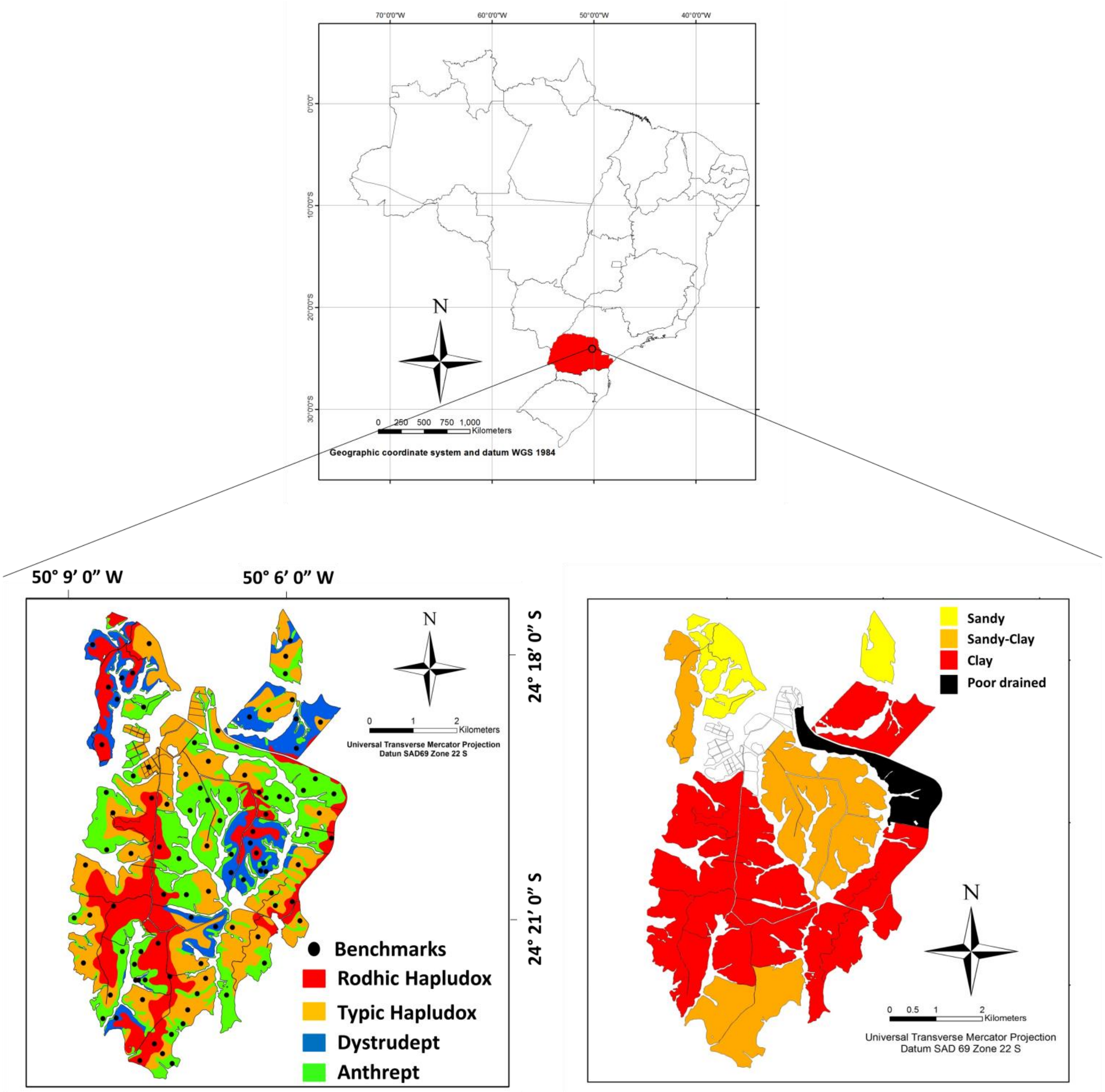

Figure 14: Map with Paiquerê farm localization, soil types, sampling point and the soils grouped according to texture and drainage.

The human management of this farm started in 1967 (Figure 3.2) with the conversion of native vegetation to pasture. After 11 years of extensive livestock production, in 1978 the pasture was converted to rice-based system with soil plowed as conventional tillage. Later in 1984 the rice-based systems were converted to no-till with best management practices and crop rotation was used composing three successions, wheat (Triticum aestivium L.)/ soybean (Glycine max L.), wheat/soybean for the second year and oat (Avena sativa L.)/ maize (Zea Mayz L.). The average biomass input for wheat/soybean was 11.5 Mg ha^{-1} year^{-1} and for oat/maize system the biomass input was 20.5 Mg ha^{-1} year^{-1} (Table 3.1), which provided the mean annual biomass input of 14.5 Mg ha^{-1} year^{-1} (Table 3.1). The fertilization of the farm plots ranged from 180 – 200 kg N ha^{-1}, 100 – 120 kg P_2O_5 ha^{-1} and 90 – 120 kg K_2O ha^{-1} for oat/maize and 100 – 120 kg ha^{-1} N, P_2O_5 and K_2O for wheat/soybean. Lime and gypsum were applied every 3 years ranging at the rate of 4 and 2–3 Mg ha^{-1} respectively and micronutrients were applied during crops development.

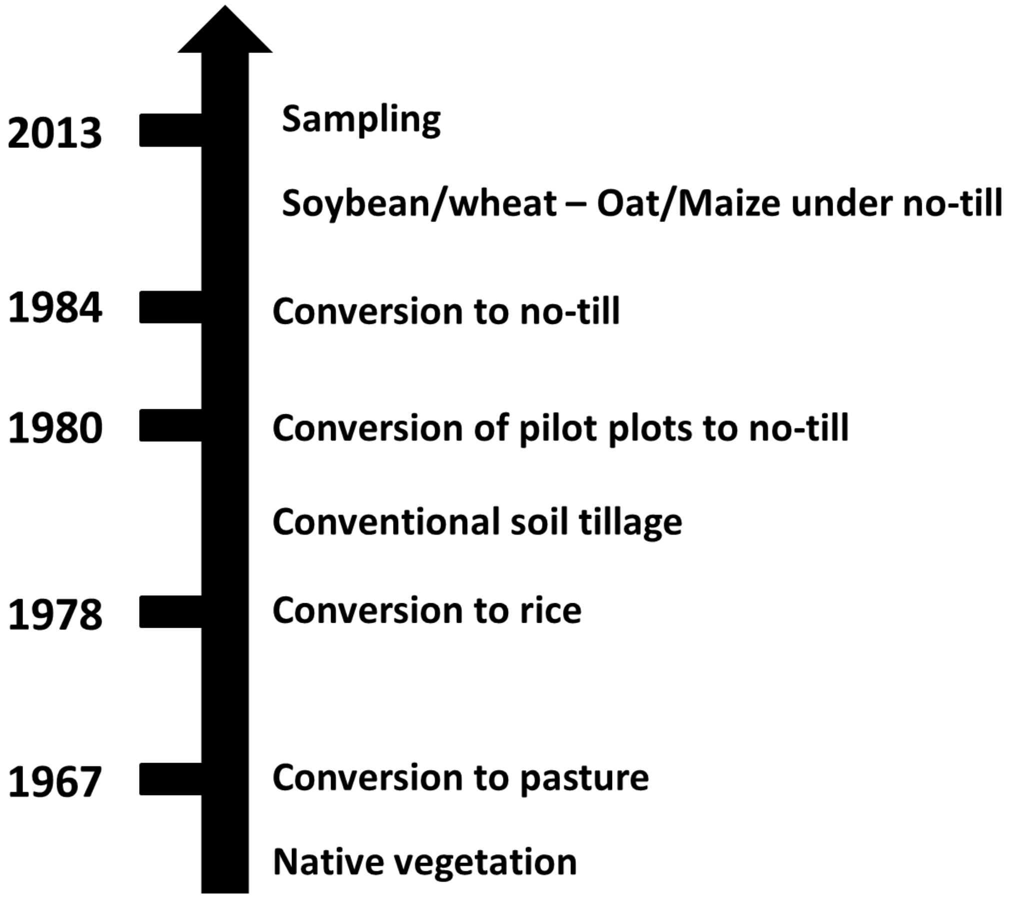

Figure 15: Historic land use change in Paiquerê farm.

Table 3.1: Historical grain yield, aboveground and belowground biomass C input in Paiquerê farm.

Year	Culture	Grain yield	Aboveground biomass	Belowground biomass	Aboveground carbon	Belowground carbon	Total carbon input
		Mg ha^{-1}					
97/98	Soybean	3.21	4.81	1.54	1.90	0.61	2.51
	Wheat	3.66	4.48	1.93	2.01	0.87	2.88
	Maize	7.24	8.85	2.82	4.03	1.28	5.31
98/99	Soybean	3.25	4.88	1.56	1.93	0.61	2.54
	Wheat	3.17	3.88	1.68	1.75	0.75	2.50
	Maize	6.38	7.80	2.49	3.55	1.13	4.68
99/2000	Soybean	3.11	4.67	1.49	1.84	0.59	2.43
	Wheat	2.85	3.48	1.50	1.57	0.68	2.24
	Maize	6.94	8.48	2.70	3.86	1.23	5.09
2000/2001	Soybean	3.16	4.74	1.51	1.87	0.60	2.47
	Wheat	2.20	2.69	1.16	1.21	0.52	1.73
	Maize	8.33	10.18	3.24	4.63	1.47	6.11
2001/2002	Soybean	3.35	5.03	1.61	1.99	0.63	2.62
	Wheat	4.30	5.25	2.27	2.36	1.02	3.38
	Maize	9.55	11.67	3.72	5.31	1.69	7.00
2002/2003	Soybean	3.57	5.35	1.71	2.11	0.67	2.79
	Wheat	1.29	1.57	0.68	0.71	0.31	1.01
	Maize	8.86	10.82	3.45	4.93	1.57	6.49
2003/2004	Soybean	3.41	5.11	1.63	2.02	0.64	2.66
	Wheat	4.67	5.71	2.47	2.57	1.11	3.68
	Maize	9.50	11.61	3.70	5.28	1.68	6.96
2004/2005	Soybean	3.04	4.56	1.46	1.80	0.57	2.38
	Wheat	3.14	3.84	1.66	1.73	0.75	2.47
	Maize	8.58	10.49	3.34	4.77	1.52	6.29
2005/2006	Soybean	3.35	5.03	1.60	1.99	0.63	2.62
	Wheat	3.44	4.21	1.82	1.89	0.82	2.71
	Maize	9.63	11.77	3.75	5.35	1.71	7.06

2006/2007	Soybean	3.65	5.48	1.75	2.17	0.69	2.86
	Wheat	2.97	3.63	1.57	1.64	0.71	2.34
	Maize	8.58	10.49	3.34	4.77	1.52	6.29
2007/2008	Soybean	3.01	4.51	1.44	1.78	0.57	2.35
	Wheat	2.56	3.13	1.35	1.41	0.61	2.02
	Maize	7.98	9.75	3.11	4.44	1.41	5.85
2008/2009	Soybean	3.14	4.72	1.51	1.86	0.59	2.46
	Wheat	3.55	4.34	1.87	1.95	0.84	2.79
	Maize	8.78	10.73	3.42	4.88	1.55	6.44
2009/2010	Soybean	3.29	4.93	1.57	1.95	0.62	2.57
	Wheat	2.06	2.52	1.09	1.13	0.49	1.62
	Maize	10.28	12.56	4.00	5.71	1.82	7.53
2010/2011	Soybean	4.04	6.06	1.93	2.39	0.76	3.16
	Wheat	4.40	5.37	2.32	2.42	1.04	3.46
	Maize	10.31	12.60	4.01	5.73	1.83	7.56
2011/2012	Soybean	3.50	5.25	1.68	2.07	0.66	2.74
	Wheat	3.11	3.80	1.64	1.71	0.74	2.45
	Maize	10.40	12.72	4.05	5.79	1.84	7.63
2012/2013	Soybean	4.01	6.01	1.92	2.37	0.76	3.13
	Wheat	3.64	4.45	1.92	2.00	0.87	2.87
	Maize	10.48	12.81	4.08	5.83	1.86	7.68
Total		246.90			138.96	47.47	186.43

*The total biomass input in the farm also include oat crop that precede maize during the winter.

The predominant soil types (Figure 3.1) at Paiquerê farm are Rodhic Hapludox USDA - (SOIL SURVEY, 2014), equivalent to Latossolo Vermelho in Brazilian classification (SOLOS, 1999), Typic Hapludox USDA - (SOIL SURVEY, 2014) equivalent to Latossolo Vermelho Amarelo (SOLOS, 1999), Inceptisol Anthrept USDA - (SOIL SURVEY, 2014) equivalent to Cambissolo Húmico (SOLOS, 1999) and Inceptisol Dystrudept USDA - (SOIL SURVEY, 2014) equivalent to Cambissolo Háplico (SOLOS, 1999). The climate is cfb according to Köppen classification (MAACK, 1981) with mean precipitation of 1717 mm distributed along the year without the presence of a dry season. The mean temperatures range between 13.5 °C in winter and 25.9 °C in summer, comprising an annual mean temperature of 17.8 °C. The native vegetation prior to conversion to agricultural land was grasslands of C_4 species.

3.2.2 Soil sampling procedure and farm database

In the Farm's database, soil samples were collected every two years between 2001 and 2009 and annually between 2009 and 2013, each time one third or 33% of the farm (1026 ha) was sampled. The exchangeable content of soil Ca^{2+}, Mg^{2+} and Al^{3+} were extracted with 1 mol L^{-1} KCl solution. After, Al^{3+} was determined by titration with 0.025 mol L^{-1} and NaOH, Ca^{2+} and Mg^{2+} by titration with 0.025 mol L^{-1} EDTA. Soil exchangeable P and K^+ were extracted with Melich-1 solution P was determined by colorimetry and determined K^+ by flame photometry. Soil pH was determined in a 0.01 mol L^{-1} $CaCl_2$ suspension (1:2.5 v/v soil/solution) and soil texture was determined by the densimeter method using a Bouyoucous scale (GEE et al., 1986). The average farm bulk density of 1.13 Mg m^{-3} (Table 3.2) was used to calculate SOC stocks using Eq 1.

$$\text{SOC (Mg ha}^{-1}\text{)} = \text{Bd (Mg m}^{-3}\text{)} * \text{d (m)} * \text{SOC (kg kg}^{-1}\text{)} * \text{SA (m}^2\text{ ha}^{-1}\text{)} \qquad (1)$$

Where: Bd = Bulk density, d = soil depth and SA = surface area.

Table 3.2: Characteristics of Paiquerê farm soil grouped according to texture and drainage.

Soil groups	Clay	Silt	Sand	Bulk Density
	-----------	g kg^{-1}	-----------	g cm^{-3}
Farm	$570_{\pm155}$	$190_{\pm105}$	$240_{\pm179}$	$1.13_{\pm0.07}$
Sandy	$260_{\pm55}$	$140_{\pm41}$	$600_{\pm51}$	$1.29_{\pm0.03}$
Sandy-Clay	$440_{\pm145}$	$210_{\pm98}$	$350_{\pm133}$	$1.18_{\pm0.06}$
Clay	$600_{\pm113}$	$300_{\pm82}$	$100_{\pm126}$	$1.09_{\pm0.05}$
Poor drained	$600_{\pm118}$	$300_{\pm122}$	$100_{\pm21}$	$1.09_{\pm0.03}$

In 2013, the farm was sampled to 1 m depth, collecting disturbed and undisturbed samples in all soil types and textural gradients comprising 98 sampling plots (Figure 3.1). The sample collection followed the following procedure (GONÇALVES et al. 2017):

i) A total of 98 marked plots of 30 x 30 m designated the benchmarks that represented each soil type, topographic position (top, half slope and foothills) and soil texture class were define in GIS environment; ii) within each benchmark plots soil samples were collected at 0-10, 10-20, 20-40, 40-70, 70-100 cm depth intervals, five subsamples per depth to make a composite sample; iii) the undisturbed samples were collected using a volumetric steel ring (5 × 5 cm) inserted in the middle of each layer in two points within each benchmark.

The bulk soil samples were oven dried at 40 ºC and grinded to pass through a 2 mm sieve, and soil cores were oven-dried at 105 ºC for 48 to 72 h. The bulk density was computed as weight:volume ratio and expressed as Mg m^{-3} using the core method (GROSSMAN and REINSCH, 2002). The samples were analyzed for C and N contents using an elemental CN analyzer (Truspec CN LECO®2006, St. Joseph, EUA) and the SOC stocks were calculated using Eq. 1.

3.2.3 Century and Roth-C model initialization

The initialization, calibration and validation of Century model (GONÇALVES et al. 2017) followed the sequence:

i) Initialization of “site.100” with farm’s latitude, longitude, monthly mean precipitation, minimum and maximum temperature obtained from farm’s meteorological station and soil texture for the first 20 cm (Table 3.2);

ii) Initialization and calibration of “Crop.100” files using mean crop yields for maize, soybean and wheat from farm’s database. We used indices “yield/shoot” and “root/shoot” obtained from Sá et al. (2014) and Villarino et al. (2014) to estimate the amount of root and shoot biomass-C input from all the crops and assumed no changes in these indexes over time.

The biomass-C input from black oats and rice were obtained from the literature (FAGERIA, 2000; SÁ et al., 2014);

iii) Validation of grain yield, root and shoot C simulations. For this the output variables of economic yield of C in grain + tubers for grass/crop “cgrain”, C in aboveground live biomass for grass/crop, “aglivc” and C in belowground live biomass for grass/crop, “bglivc” were used;

iv) Initialization of “schedule” file with the historical farm management. We used the files “cult.100”, “fert.100”, “fire.100”, “fix.100”, “graz.100” and “harv.100” within “default” values from Century;

v) Calibration of the simulations by altering native vegetation C input. The mean estimation error for SOC stocks simulation was -9.54 Mg C ha^{-1} and the mean root mean square error (RMSE) was 23.1 Mg C ha^{-1}.

The Roth-C model was initialized as follows:

i) The “weather.dat” file was edited using mean temperature, precipitation and evaporation data from the farm meteorological station and the mean clay content of farm’s soils, 560.7 g kg^{-1} for the first 20 cm depth was used.

ii) The “scenario.set” file was edited in “equilibrium mode” with a decomposable/resistant plant material (DMP/RMP) ratio of 1.44, default value of Roth-C for most crops and improved grasslands. Inert organic matter of 2.98 Mg ha^{-1}, obtained from Falloon et al. (2000) equation was used until 1967, year of the native vegetation conversion to pasture system. After in “short term” mode, all the historic events that occurred on the farm (Figure 3.2) were added for the simulations.

iii) The “land management.dat” file was edited considering the soil was covered all over the year with no manure additions for no-till. The input of crop residues was calculated according to root/shoot and grain yield/shoot indices reported in Sá et al. 2014 and Villarino et al. (2014), we assumed no changes in these indices over time, and using the crop yields from the farm’s database (Table 3.1). The native vegetation, pasture and conventional till rice-based residue input were obtained from the literature (FAGERIA, 2000; PILLAR et al., 2009). To simulate land use conversion with Roth-C model, the biomass-C input was stopped, and the soil was considered fallow for one year.

3.2.4 Soil organic carbon dynamics simulations

After the initialization, Century and Roth-C models were used to simulate the SOC pools dynamics of the farm from 1967 to 2015. The simulated pools were total, slow, active and passive soil carbon pools for Century; and total, humine and microbial biomass carbon pools for Roth-C.

To access the effect of biomass-C input on the SOC storage, dynamics and saturation, the files potential aboveground monthly production “PRDX” from crop.100 of Century and land management.dat of Roth-C were adjusted to simulate a) existing farm biomass input (14.5 Mg ha^{-1} year^{-1}) or C input (6.5 Mg ha^{-1} year^{-1}); b) 15% increase of farm biomass input (16.7 Mg ha^{-1} year^{-1}) or C input (7.5 Mg ha^{-1} year^{-1}); c) 15% decrease of farm biomass (12.3 Mg ha^{-1} year^{-1}) or C input (5.5 Mg ha^{-1} year^{-1}) and, d) 30% decrease of farm biomass input (10.1 Mg ha^{-1} year^{-1}) or C input (4.5 Mg ha^{-1} year^{-1}). Simulations were performed in three intervals of 20 year periods, comprising 2015 – 2035, 2035 – 2055 and 2055 – 2075.

3.2.5 Crop yields evolution in the farm

The crop yield data for maize (Zea mays), soybean (Glycine max) and wheat (Triticum aestivum) were obtained from 1997 - 2013 as yield maps using John Deere combines sensors with Greenstar GPS integrated systems (Table 3.1). The mean precipitation in summer and winter periods, obtained from the farm meteorological station (GONÇALVES et al., 2015) were plotted with the crop yields to study the linear relationships between precipitation and crop yields. In addition, correlation matrixes comprising all soil fertility attributes, crop yields and precipitation were generated and used to explore the variables relationships.

3.2.6 Geospatial analysis and expansion of the results

We stratified the farm SOC stock data for three-time periods (2015 – 2035, 2035 – 2055 and 2055 – 2075) using soil texture (Groups 1, 2 and 3) and drainage condition (Group 4) in the GIS environment (Figure 3.1, Table 3.2). This procedure was used as soil texture and drainage condition were the factors that most affected SOC stock distribution in the farm (GONÇALVES et al., 2015). We chose Century model to scale up our findings as it produced lower prediction errors in comparison to Roth-C to simulate SOC stocks in Paiquerê farm.

We used the results from Paiquerê Farm to expand for other croplands (assuming similar crop management conditions), obtained from a 250 m resolution world land cover map (BONTEMPS et al., 2011), with similar climate (cf) (RUBEL and KOTTEK, 2010) and soil types (low activity clay) (PACHAURI et al., 2014) globally (Figure 3.3). We compared the crop yield gain with the current world crop yield estimation obtained from the database of USDA (2016). For the SOC stocks, we made the comparison with the current SOC stocks estimated for the same area (Figure 3.3) using Batjes (2015) maps and a mean soil bulk density of 1.2 Mg m^{-3}. We used the measured SOC stocks (to 1 m depth) in 2013 to extend the estimate to 1 m, beyond Century simulations for 0-20 cm. For all the spatial analysis and scaling up we used the software ArcGIS v. 10.4.1 (ESRI, 2017).

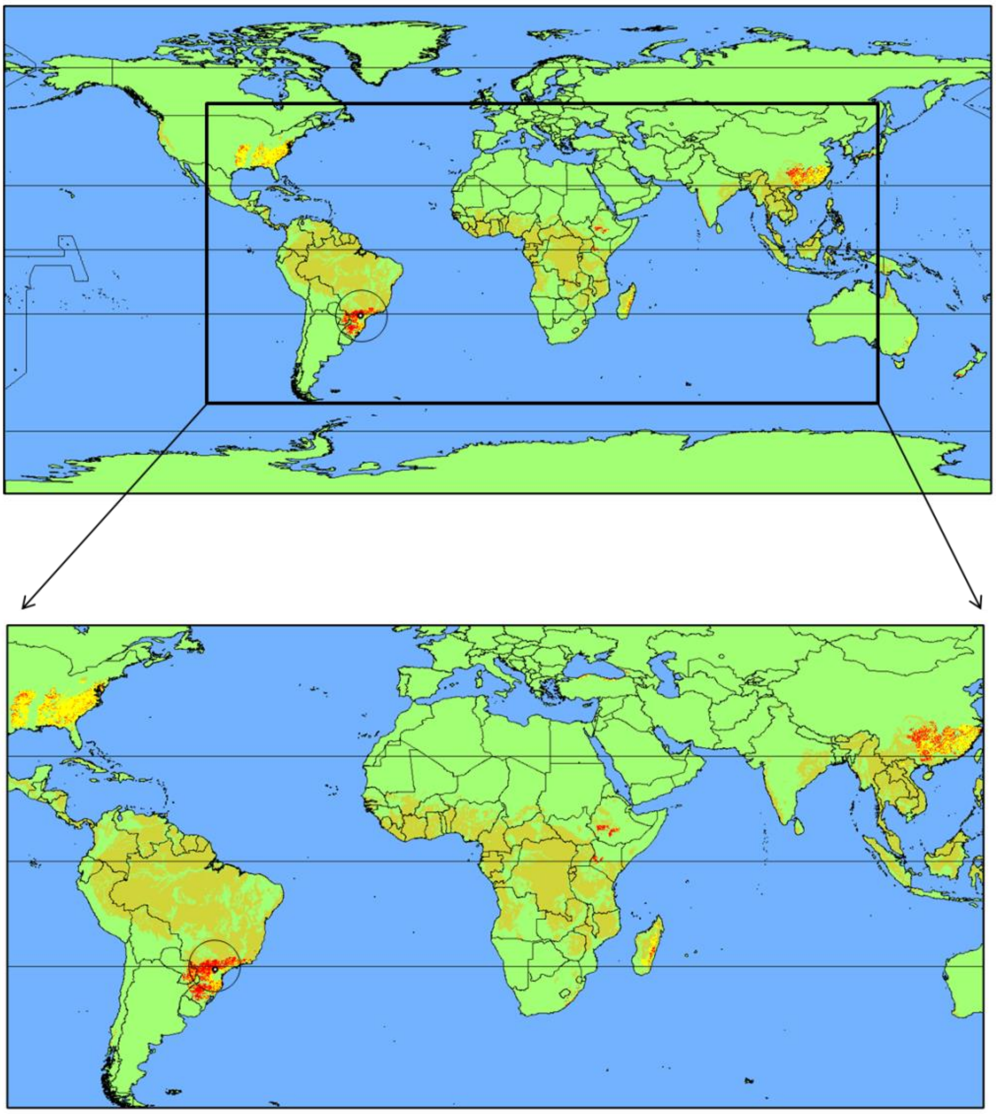

Figure 16: World croplands with similar climatic and soil characteristics of the farm.
Yellow = Sub-tropical climate (Cf according to Köppen classification); Orange = Low activity clay soils (LCA according to IPCC, 2010); Red = Croplands in intersection between both, equivalent to 861.643 Km^2; White point in the circle = Location of Paiquerê farm.

3.2.7 Uncertainty analysis

We estimated the uncertainty in observed SOC stocks through the calculation of ±1 standard deviations. In addition, we assessed the uncertainty associated with the input variables and Century model structure, that were used for scaling up the modeled results, using an empirical method described in Ogle et al. (2007) and Monte Carlo simulations (OGLE et al., 2010; PACHAURI et al., 2014). Briefly: i) We performed a multiple linear regression fitting measured SOC stocks as a function of simulated SOC, soil texture, soil bulk density and crop yield; ii) The variables with a p value < 0.05 (simulated SOC and soil texture) were tested for normality with Shapiro-Wilk test and considered for the uncertainty calculation; iii) We used a means vector (μ) and covariance matrix (σ) to generate a multivariate normal distribution and performed Monte Carlo simulation (n=100) for the selected variables; iv) The intercept and coefficients of the multiple linear regression and the simulated variables were used to run the equation 100 times. This process accounts for the variability of input variables (soil texture) and model structure (simulated SOC); v) The 95% confidence intervals were calculated using Eq. 2.

$$\mu \pm 1.96 * \sigma/\sqrt{n} \qquad (2)$$

Where: 1.96 is the standard z value for 95% confidence interval; σ is the standard deviation of SOC and n is the Monte Carlo simulation numbers (100). The uncertainties calculated for the simulations were accounted in the predictions and expansions, and other sources of uncertainties were highlighted in the discussion section. For the uncertainty calculation software R v. 3.4.0 (R CORE TEAM, 2017) was used. A schematic representation of the methodology is show in figure 3.4.

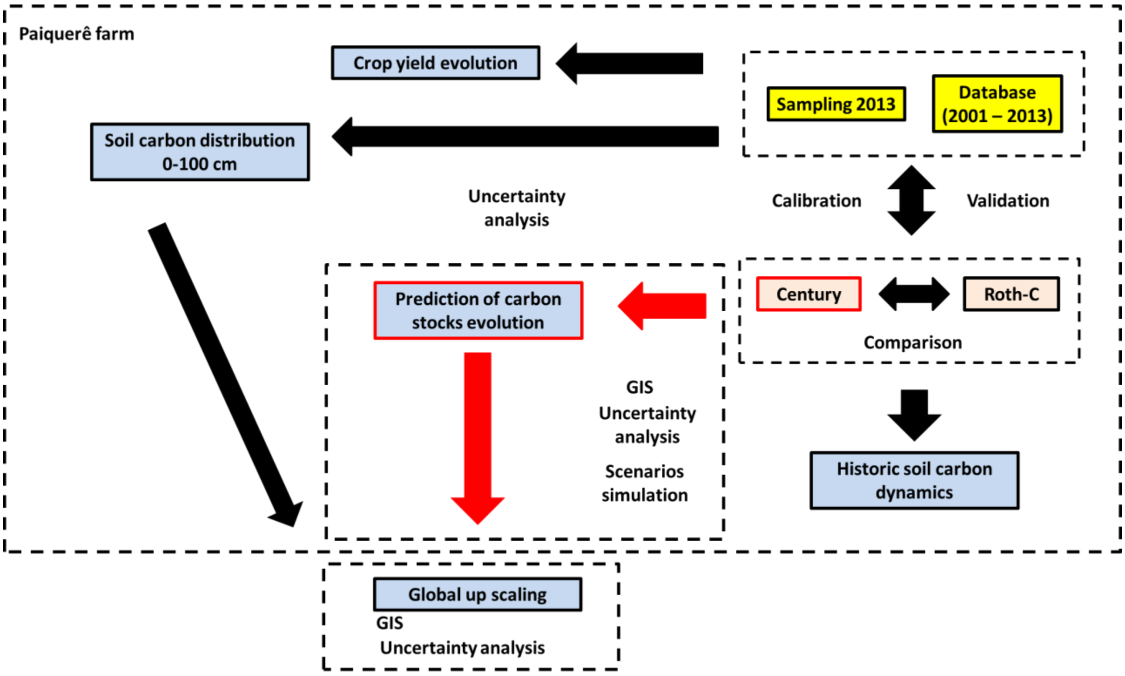

Figure 17: Schematic methodology adopted in this study, the red squares and arrows indicate steps were just Century model was used.
Yellow boxes = Data, Pink boxes = Models, Blue boxes = Results, No boxes text = Analysis and process.

3.3 RESULTS

3.3.1 Soil organic carbon dynamics in Paiquerê farm

The Century model simulations estimated SOC stock of 83 Mg ha^{-1} when the soil was under native vegetation (Figure 3.5). During the conversion to pasture by slash and burn, the SOC stocks increased to 97 Mg ha^{-1}, and stabilized at 82 Mg ha^{-1}, similar to initial values. The initial conversion of pasture to conventional tillage by soil plowing increased the SOC stocks to 100 Mg ha^{-1}. However, continuing conventional tillage-based rice system reduced SOC stocks to 69 Mg ha^{-1} in 6 years, at a rate of 2.16 Mg ha^{-1} yr^{-1}. Adoption of no-till stimulated the SOC enhancement, and SOC stock increased at a rate of 0.4 Mg ha^{-1} yr^{-1} for the first and 0.13 Mg ha^{-1} yr^{-1} for the second decades, respectively. After 30 years of no-till the Century model indicated that SOC stocks reached a new equilibrium at 74 Mg ha^{-1}.

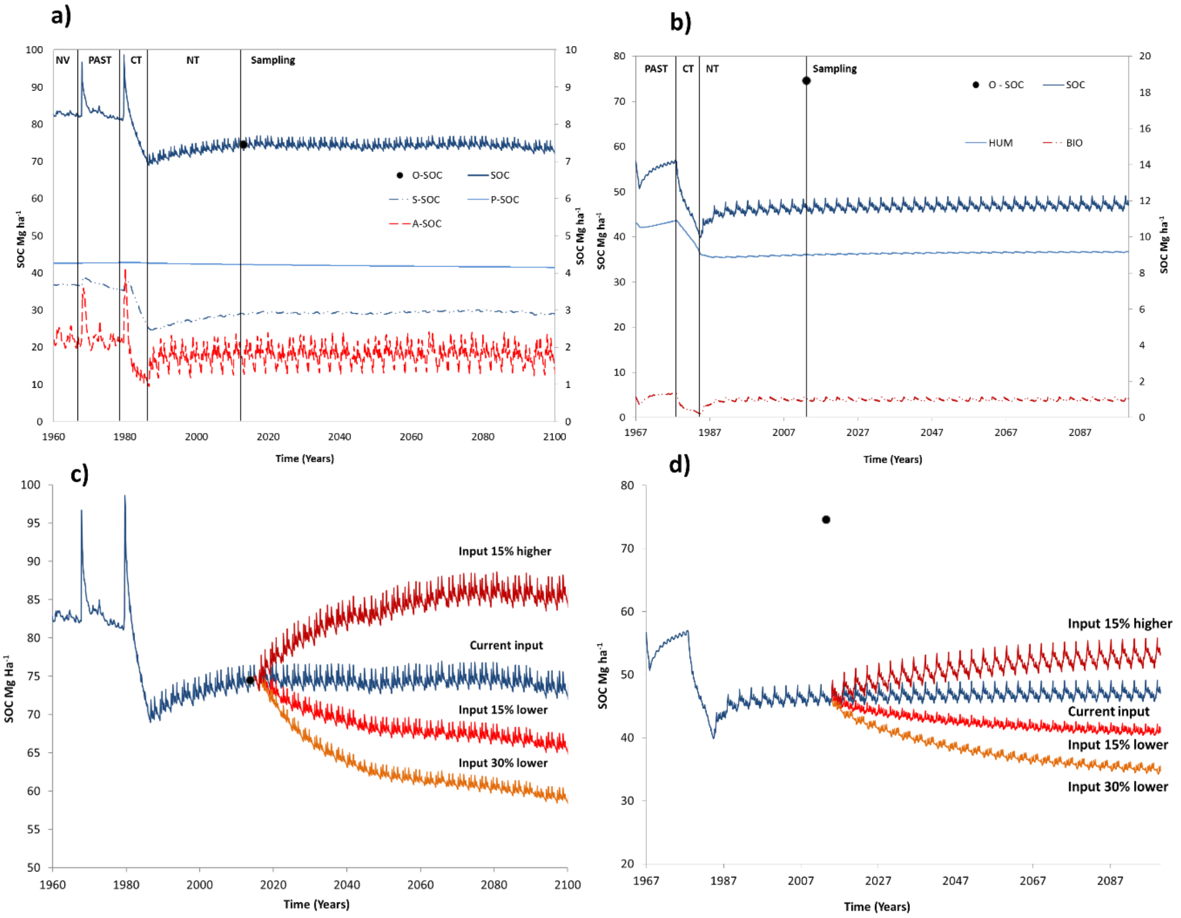

Figure 18: Dynamics of total and SOC pools in Paiquerê farm assessed by Century **(a)** and Roth-C models **(b)**. Effect of residue C input increase and decrease assessed by Century **(c)** and Roth-C **(d)** in Paiquerê farm.

*Plotted in **(a)** and **(b)** primary axis: SOC = Soil organic carbon; O-SOC = Observed SOC; P-SOC = Passive SOC; HUM = Humine.

*Plotted in **(a)** and **(b)** secondary axis: S-SOC = Slow SOC; A-SOC = Active SOC; BIO = Microbial biomass C.

The passive SOC pool remained stable at 42 Mg ha^{-1} during the entire period (1967 – 2100). The active SOC pool increased to 3.6 and 4 Mg ha^{-1} during conversion from native vegetation to pasture, and pasture to conventional tillage, respectively. In the other periods, active SOC pool remained stable at 2 Mg ha^{-1}. The Slow SOC pool was at 36 Mg ha^{-1} during native vegetation, and it increased to 39 and 38 Mg ha^{-1} during the conversion of native vegetation to pasture and pasture to conventional tillage, respectively. The slow SOC pool stabilized at 29 Mg ha^{-1} after 30 years of no-till adoption.

The Roth-C model showed similar SOC dynamics as predicted by Century model, however the absolute values were underestimated (Figure 3.5). The SOC stock was at 55 Mg ha^{-1} under native vegetation which decreased to 50 Mg ha^{-1} during the conversion of native vegetation to pasture and increased to 55 Mg ha^{-1} under pasture until the second conversion, from pasture to conventional tillage. During conventional tillage the SOC stocks depleted at a rate of 3.2 Mg ha^{-1} yr^{-1}. No-till increased the SOC stocks at a rate of 0.7 Mg ha^{-1} yr^{-1} during the first decade stabilizing at a new equilibrium stage of 47 Mg ha^{-1}.

The active SOC pool remained at 0.9 Mg ha^{-1} during the entire period just changing according to the seasonal fluctuations in soil moisture and temperature. During the first conversion of native vegetation to pasture and to conventional tillage, the active SOC pool decreased to 0.7 Mg C ha^{-1} and 0.1 Mg C kg^{-1}, respectively. Also, the resistant plant material decreased from 9 to 5 Mg C ha^{-1} during the conversion of native vegetation to pasture, however, under no-till it increased and stabilized at 6.2 Mg ha^{-1}.

3.3.2 Crop yields evolution in the farm

Crop productivity increased from 1998 to 2013; for maize the increase was 44% (3150 kg ha^{-1}) at the annual rate of 210 kg ha^{-1} yr^{-1} (Figure 3.6). Soybean production increased 16% (510 kg ha^{-1}) at the annual rate of 34 kg ha^{-1} yr^{-1}. Similarly, wheat production increased 6% (240 kg ha^{-1}) at the rate of 16 kg ha^{-1} yr^{-1}.

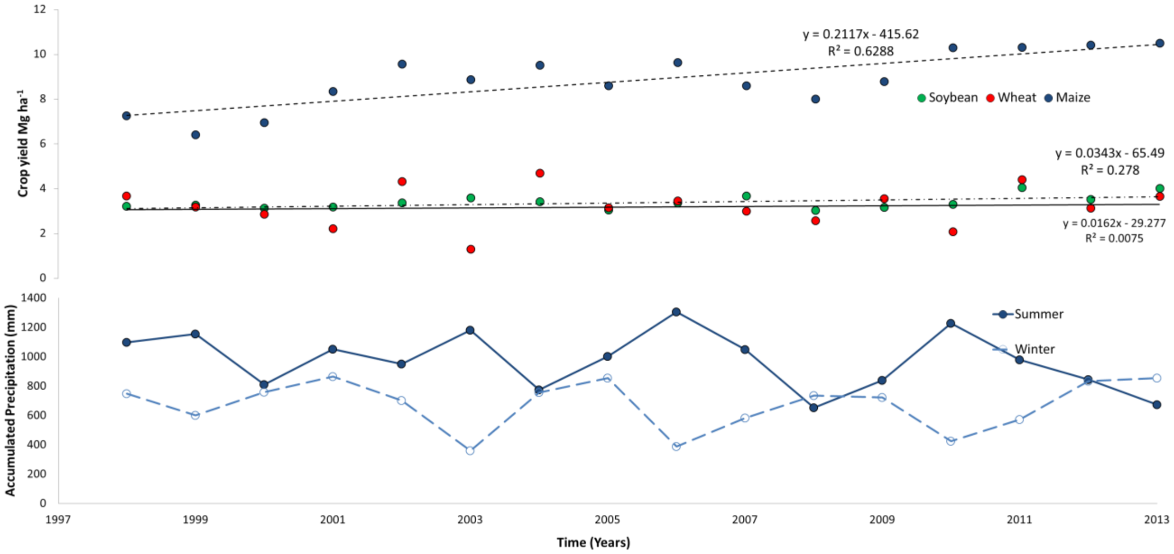

Figure 19: Crop yield evolution and accumulated summer and winter precipitation between 1998 and 2013 in Paiquerê farm.

As the soils of the farm do not present fertility limitations (GONÇALVES et al., 2017) and the fertilization was performed to keep the nutrient stocks appropriate, the water availability and the bulk density, which influence crop roots development, can be the soil attributes that most influenced the crop yield. This can be observed in Table 3.3, where crop yield did not show correlations with soil fertility attributes, indicating that soil fertility is not a limiting factor. On the other hand, wheat and maize showed medium correlations with precipitation. Soil C presented a high affinity with CEC, demonstrating its importance to keep appropriate soil fertility levels.

Table 3.3: Pearson correlation matrix with soil fertility attributes (0-20 cm), precipitation and crop yield obtained from farm database between 2001 and 2013. The first table refers to all data without crop yields, the second, third and fourth include crop yields of soybean, wheat and maize respectively.

	P	**C**	**pH**	**Al**	**H+Al**	**Ca**	**Mg**	**K**	**BS**	**ECEC**
C	0.14									
pH	0.01	0.02								**n=1951**
Al	-0.01	0.02	- 0.31							
H+Al	-0.04	0.38	-0.35	**0.74**						
Ca	0.35	0.54	0.21	-0.33	-0.24					
Mg	0.10	0.50	0.21	-0.30	-0.15	0.65				
K	0.33	0.46	0.12	-0.28	-0.12	0.56	0.40			
BS	0.31	0.57	0.23	-0.35	-0.22	**0.97**	**0.80**	0.60		
ECEC	0.32	0.61	0.16	-0.11	-0.05	**0.94**	**0.77**	0.56	**0.97**	
CEC	0.23	**0.76**	-0.09	0.29	0.59	0.62	0.54	0.40	0.65	**0.77**

	P	**C**	**pH**	**Al**	**H+Al**	**Ca**	**Mg**	**K**	**BS**	**ECEC**	**CEC**	**Precip**
C	0.19											
pH	0.10	0.08										**n=1862**
Al	-0.05	0.02	-0.66									
H+Al	-0.05	0.37	**-0.77**	**0.74**								
Ca	0.36	0.54	0.56	-0.37	-0.25							
Mg	0.12	0.48	0.51	-0.31	-0.16	0.67						
K	0.32	0.46	0.36	-0.33	-0.14	0.54	0.38					
BS	0.32	0.56	0.58	-0.38	-0.24	**0.97**	**0.80**	0.57				
ECEC	0.33	0.60	0.46	-0.17	-0.08	**0.94**	**0.78**	0.53	**0.98**			
CEC	0.23	**0.76**	-0.09	0.24	0.56	0.63	0.57	0.38	0.67	**0.77**		
Precip	0.00	0.02	0.01	-0.04	0.13	-0.06	0.11	0.13	-0.01	-0.02	0.09	
Soybean	0.05	-0.12	-0.01	-0.02	-0.08	0.12	0.06	-0.10	0.10	0.11	0.03	-0.10

	P	**C**	**pH**	**Al**	**H+Al**	**Ca**	**Mg**	**K**	**BS**	**ECEC**	**T**	**Precip**
C	0.13											
pH	0.07	0.10										**n=1862**
Al	-0.01	0.02	-0.67									
H+Al	-0.04	0.37	**-0.77**	**0.74**								
Ca	0.28	0.55	0.56	-0.35	-0.25							
Mg	0.07	0.50	0.52	-0.32	-0.16	0.68						
K	0.24	0.44	0.32	-0.31	-0.12	0.51	0.35					
BS	0.25	0.58	0.58	-0.37	-0.24	**0.98**	**0.82**	0.54				
ECEC	0.26	0.62	0.46	-0.16	-0.08	**0.96**	**0.79**	0.50	**0.98**			
CEC	0.18	**0.77**	-0.09	0.25	0.56	0.64	0.57	0.37	0.67	**0.77**		
Precip	0.00	-0.08	0.05	0.00	-0.10	0.13	0.13	-0.24	0.13	0.13	0.03	
Wheat	0.06	0.20	0.04	-0.04	0.03	0.02	0.13	-0.01	0.05	0.05	0.07	-0.36

	P	**C**	**pH**	**Al**	**H+Al**	**Ca**	**Mg**	**K**	**BS**	**ECEC**	**CEC**	**Precip**
C	0.31											
pH	-0.05	-0.05										**n=1360**
Al	-0.01	0.08	-0.16									
H+Al	0.09	0.41	-0.19	**0.79**								
Ca	0.33	0.61	0.08	-0.46	-0.28							
Mg	0.03	0.56	0.09	-0.31	-0.12	**0.71**						
K	0.40	0.54	0.03	-0.33	-0.14	**0.70**	0.43					
BS	0.27	0.64	0.08	-0.44	-0.24	**0.97**	**0.84**	**0.70**				
ECEC	0.30	**0.72**	0.05	-0.21	-0.05	**0.94**	**0.83**	0.67	**0.97**			
CEC	0.29	**0.85**	-0.09	0.31	0.64	0.54	0.57	0.44	0.59	**0.73**		
Precip	0.15	-0.15	-0.07	0.21	0.14	-0.22	-0.29	-0.04	-0.25	-0.21	-0.08	
Maize	-0.10	-0.16	0.01	0.03	-0.03	-0.16	-0.17	-0.09	-0.17	-0.18	-0.16	0.59

Table 3.4: Soil organic carbon stocks in all the soil groups of Paiquerê farm between 2015 and 2075.

Scenario	Soil group	Observed SOC (2013) (Mg ha^{-1})	2015			2035			2055			2075		
			SOC (Mg ha^{-1})	Area (ha)	SOC (Gg)	SOC (Mg ha^{-1})	Area (ha)	SOC (Gg)	SOC (Mg ha^{-1})	Area (ha)	SOC (Gg)	SOC (Mg ha^{-1})	Area (ha)	SOC (Gg)
15% higher	1		41.60±0.2	222.16	9.24±0.04	48.18±0.2	222.16	10.70±0.04	49.84±0.2	222.16	11.07±0.04	50.69±0.2	222.16	11.26±0.04
	2		61.38±0.2	119.12	7.31±0.02	68.91±0.2	119.12	8.21±0.02	71.03±0.2	119.12	8.46±0.02	72.29±0.2	119.12	8.61±0.02
	3		85.84±0.2	2524.34	216.69±0.5	94.09±0.2	2524.34	237.52±0.5	96.89±0.2	2524.34	244.58±0.5	98.31±0.2	2524.34	248.17±0.5
	PD		111.13±0.2	212.47	23.61±0.04	120.98±0.2	212.47	25.70±0.04	124.31±0.2	212.47	26.41±0.04	127.64±0.2	212.47	27.12±0.04
Total					256.85±0.5$^{£}$			282.13±0.5			290.53±0.5			295.16±0.5
World			62.94±0.2	86.2 (Mha)	5.4±0.02 (Pg)	70.39±0.2	86.2	6.06±0.02	72.59±0.2	86.2	6.25±0.02	73.76±0.2	86.2	6.35±0.02
Current	1	$44.5_{\pm 11.9}$	41.60±0.2	222.16	9.24±0.04	41.79±0.2	222.16	9.28±0.04	41.85±0.2	222.16	9.30±0.04	41.85±0.2	222.16	9.30±0.04
	2	$74.59_{\pm 16.2}$	61.38±0.2	119.12	7.31±0.02	61.56±0.2	119.12	7.33±0.02	61.51±0.2	119.12	7.33±0.02	61.44±0.2	119.12	7.32±0.02
	3	$75.77_{\pm 13.1}$	85.84±0.2	2524.34	216.69±0.5	86.02±0.2	2524.34	217.14±0.5	86.02±0.2	2524.34	217.14±0.5	85.74±0.2	2524.34	216.44±0.5
	PD	$105.8_{\pm 13.3}$	111.13±0.2	212.47	23.61±0.04	113.00±0.2	212.47	24.01±0.04	113.17±0.2	212.47	24.05±0.04	113.57±0.2	212.47	24.13±0.04
Total					256.85±0.5			257.77±0.5			257.81±0.5			257.18±0.5
World			62.94±0.2	86.2	5.4±0.02	63.12±0.2	86.2	5.44±0.02	63.13±0.2	86.2	5.44±0.02	63.01±0.2	86.2	5.43±0.02
15% lower	1		41.60±0.2	222.16	9.24±0.04	37.69±0.2	222.16	8.37±0.04	36.43±0.2	222.16	8.09±0.04	36.24±0.2	222.16	8.05±0.04
	2		61.38±0.2	119.12	7.31±0.02	57.00±0.2	119.12	6.79±0.02	55.44±0.2	119.12	6.60±0.02	54.91±0.2	119.12	6.54±0.02
	3		85.84±0.2	2524.34	216.69±0.5	80.51±0.2	2524.34	203.23±0.5	78.52±0.2	2524.34	198.21±0.5	77.56±0.2	2524.34	195.79±0.5
	PD		111.13±0.2	212.47	23.61±0.04	107.09±0.2	212.47	22.75±0.04	104.65±0.2	212.47	22.24±0.04	103.65±0.2	212.47	22.02±0.04
Total					256.85±0.5			241.15±0.5			235.14±0.5			232.40±0.5
World			62.94±0.2	86.2	5.4±0.02	58.40±0.2	86.2	5.03±0.02	56.80±0.2	86.2	4.89±0.02	56.24±0.2	86.2	4.84±0.02
30% lower	1		41.60±0.2	222.16	9.24±0.04	34.62±0.2	222.16	7.69±0.04	32.72±0.2	222.16	7.27±0.04	32.16±0.2	222.16	7.14±0.04
	2		61.38±0.2	119.12	7.31±0.02	52.88±0.2	119.12	6.30±0.02	50.37±0.2	119.12	6.00±0.02	49.38±0.2	119.12	5.88±0.02
	3		85.84±0.2	2524.34	216.69±0.5	74.85±0.2	2524.34	188.95±0.5	71.15±0.2	2524.34	179.61±0.5	69.62±0.2	2524.34	175.74±0.5
	PD		111.13±0.2	212.47	23.61±0.04	101.60±0.2	212.47	21.59±0.04	97.25±0.2	212.47	20.66±0.04	95.23±0.2	212.47	20.23±0.04
Total					256.85±0.5			224.52±0.5			213.54±0.5			209.01±0.5
World			62.94±0.2	86.2	5.4±0.02	54.12±0.2	86.2	4.66±0.02	51.41±0.2	86.2	4.43±0.02	50.39±0.2	86.2	4.34±0.02

£ = 95% confidence interval.

3.3.3 Effect of biomass-C input on soil organic carbon stocks

In the scenario of 15% increase in biomass-C input, Century model simulated increase in SOC stock at a rate of 0.21 Mg ha^{-1} yr^{-1} during the first 60 years (Figure 3.5, Table 3.4) and SOC stocks stabilized at 85 Mg ha^{-1}. However, when biomass-C input decreased by 15%, the SOC stock decreased at a rate of 0.2 Mg ha^{-1} yr^{-1} during the first two decades. In the scenario of 30% of biomass-C input decrease, the SOC stock decreased at 0.5 Mg ha^{-1} yr^{-1} during the first two decades, and at 0.17 Mg ha^{-1} yr^{-1} for next four decades, not reaching an equilibrium.

In the scenario of 15% biomass-C input increase, Roth-C model simulated increase in SOC stock at 5 Mg C ha^{-1} yr^{-1} during the first 30 years, and SOC stocks stabilized at 52 Mg ha^{-1}. However, the decrease of 15% of biomass-C input, decreased the SOC stocks at 5 Mg ha^{-1} in 60 years, and stabilized at 41 Mg ha^{-1}. We observed that the SOC stocks decreased two times slower than the increase with 15% more crop residue. With a 30% decrease in residue C input, the SOC stocks decreased at 0.17 Mg ha^{-1} year^{-1} during first 40 years, then it decreased at 0.05 Mg ha^{-1} year^{-1} during the last 20 years, not reaching an equilibrium.

3.3.4 Spatial analysis and results expansion

With the current biomass-C input, the SOC stocks in all soil groups are in steady-state and SOC stocks will slightly increase (0.33 Gg C) until 2075 (Table 3.4). With a 15% decrease in biomass-C input the SOC stocks will be reduced by 9% (24.45 Gg C), and with 30% decrease in biomass-C input the SOC stocks will decrease by 18% (47.84 Gg C). The SOC decrease will be more drastic in soil group 1 (23%), compared to soil groups 2 (20%), 3 (19%) and poorly drained (15%) respectively. However, with a 15% increase in biomass-C input the SOC stocks will increase by 16% (38.31 Gg C). The increase will be greater in group 1 (22%), compared to groups 2 (18%), 3 (15%) and poorly drained soils (15%).

Table 3.5: Expansion of the results to total global land area.

	Crop yield (Mg ha^{-1})			Crop yield (Tg)				Reference
	World	Paiquerê farm	Delta	World	Paiquerê farm	Delta		
Maize	5.6	$10.5_{\pm 3.6}$	$4.84_{\pm 3.6}$	482.5	$904.7_{\pm 310.2}$	$422.2_{\pm 310.2}$		USDA, (2016)
Soybean	2.7	$4.0_{\pm 0.2}$	$1.31_{\pm 0.2}$	232.6	$344.7_{\pm 17.2}$	$112.0_{\pm 17.2}$		USDA, (2016)
Wheat	3.3	$3.6_{\pm 0.6}$	$0.35_{\pm 0.6}$	284.3	$310.2_{\pm 51.7}$	$25.8_{\pm 51.7}$		USDA, (2016)
				SOC (Pg)				
				Current	Paiquerê no-till (2075)	Delta	Delta (CO_2)	
Current				2.86	$5.4\pm0.02^{£}$	2.54 ± 0.02	9.14 ± 0.07	ISRIC, (2012)
More 15% residue C				2.86	6.3 ± 0.02	3.44 ± 0.02	12.38 ± 0.07	ISRIC, (2012)

*The expansion were done bases in a total world area of 4.007.709 Km², corresponding to Cf climate (Köppen classification) and Low activity clay soils (IPCC, 2010).

£ = 95% confidence interval.

The scaling of best management practices farming system to similar soil and climatic conditions globally, shows a potential to store 5.4±0.02 Pg C in 60 years in soils to 0-20 cm depth (Table 3.5). With 15% increase in biomass-C input this potential can increase to 6.3±0.02 Pg C. These values are 2.54±0.02 and 3.44±0.02 Pg C greater compared to the current SOC estimates using Batjes (2015) maps. This indicates a sequestration potential up to 9.14±0.07 and 12.4±0.07 Pg CO_2 in 60 years. However, considering SOC stocks of 1 m soil depth (the 0-20 cm contains 56% of the total C stocks) (Figure 3.7), the mean SOC stocks in the farm are 143±35 Mg ha^{-1}. The expansion of this result indicated that SOC stocks can be increased to 9.6±3 Pg C considering current biomass input, and 11.2±3 Pg C considering 15% increase in biomass-C input in the 0-100 cm soil depth profile, which is equivalent to a sequestration of 34.6±11 Pg CO_2 to 40.5±11 Pg CO_2 in 60 years. This is equivalent to 11 years of global land use and land use change emissions (PACHAURI et al., 2014). The Paiquerê farm yields are 11% (0.35), 49% (1.31) and 86% (4.84) Mg ha^{-1} higher for wheat, soybean and maize respectively compared to the current estimates for the world (USDA, 2016). This implies a total gain of 25.8 ± 51.7, 112.0 ± 17.2 and 422.2 ± 310.2 Tg of grains, when these results are scaled up globally.

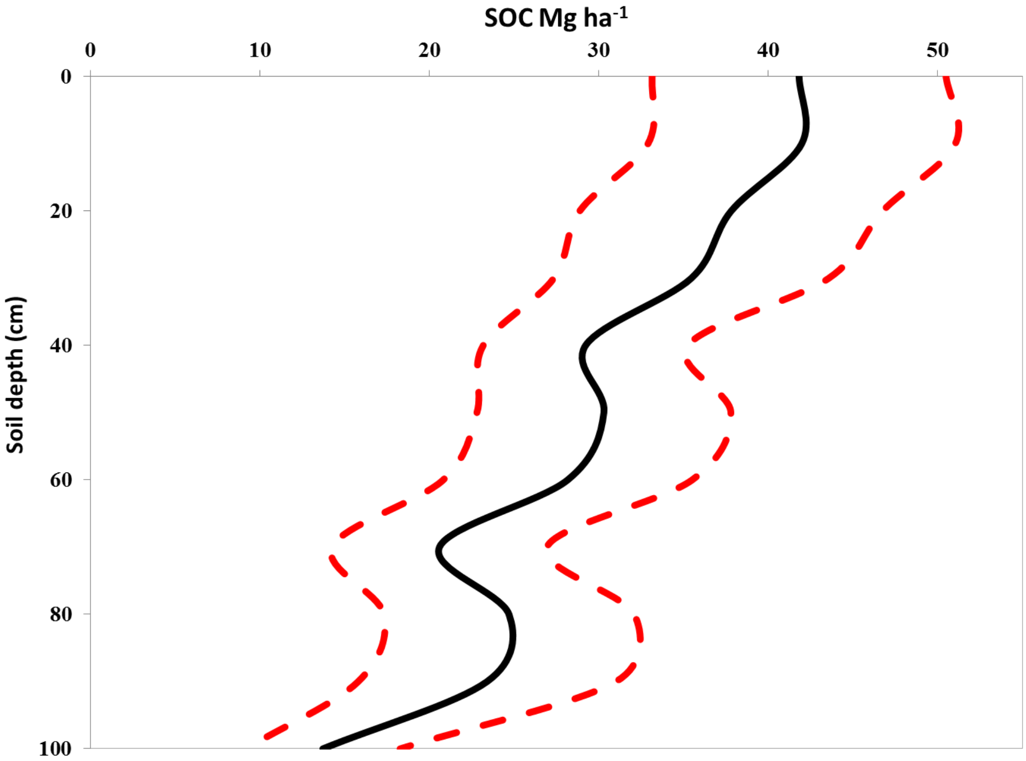

Figure 20: Vertical distribution of soil organic carbon in Paiquerê farm considering all soil types. The red dot lines represent the standard deviations intervals.

3.4 DISCUSSION

Both models indicated reduction in SOC stocks under soil tillage-based system and an increase and subsequent stabilization under no-till system. The Roth-C results were similar to Century model projections, however, the absolute SOC stock values were underestimated. This may be due to small number of mechanisms used in Roth-C (COLEMAN and JENKINSON, 1996), as Roth-C was developed to simulate Rothamsted station SOC dynamics. However, the greater number of Century model parameters (PARTON et al., 1988) made it more suitable for long term simulations and predictions across different regions.

Adoption of no-till system promoted an increase in the SOC stocks, and the increase rate during the first 2 decades (0.4 Mg ha^{-1} yr^{-1}) was similar to the other values reported for medium term (20 years) experiments, 0.19 Mg ha^{-1} yr^{-1} to 0.55 Mg C ha^{-1} yr^{-1} (FERREIRA et al., 2012; ZANATTA et al., 2007). The SOC increased (Figures 3.4 and 3.5) due to the high and constant biomass C input of the farm. The soybean/wheat crop succession promoted input of organic material with different C/N proportions (ÁLVARO-FUENTES et al., 2012) and the oat/maize crop succession where oat is a biomass crop promoted high C input, creating an agroecosystem that can sustain C increase. It is important to note that high rates of SOC increase can be sustained only with high plant biomass-C input, which influences crop yields (Table 3.3, Figure 3.6) and can be sustained by fertilization management. A recent study support these findings. Ferreira et al. (2018), studying long term no-till areas in Oxisols, reported that higher SOC stocks were associated with low Al^{3+} content and high exchangeable bases saturation.

Although part of the carbon increase can be related to crop breeding (resulting in higher productivity and biomass production over time), conservative systems played a major role in SOC stocks increase. Sá et al. (2014), studying management systems for 30 years in the same region reported higher SOC stocks for no-till system. While all the studied systems promoted increase in SOC stocks, no-till system was 20% higher compared to conventional tillage system with soil plough. The same way, Sá et al. (2001) compared different site managements and crop rotation systems and founded SOC stocks in no-till systems with 22 years to be 20% higher compared with conventional tillage systems in the same age.

Some studies showed that in addition to sustain plant production, fertilization can be the key to sustain SOC increase (KIRKBY et al., 2013; KIRKBY et al., 2014). Kirkby et al. (2013) reported that the fine SOC fraction follows the stoichiometry C:N:P:S = 10000:833:200:143, demonstrating the good fertilization management of the farm essential to promote and maintain higher SOC stocks. The fertilization management also influences the C stabilization process. Briedis et al. (2012) showed a close relationship between Ca and SOC, using energy disperse x-ray spectroscopy in soil macroaggregates. Consistent with this result, our data (Table 3.3) showed medium correlation between SOC and Ca content. Although Al is important for C stabilization during organo-mineral interactions, in croplands with intense liming the Ca can substitute Al as the cationic bridge (BRIEDIS et al., 2012, INAGAKI et al., 2017, FERREIRA et al. 2018).

Other factor that explains the high C stabilization in tropical and sub-tropical soils is the presence of Fe and Al oxides (SAIDY et al., 2012). The anion exchange capacity of oxides allows the direct stabilization of organic molecules by soil minerals without the necessity of a cation bridge. Thus, the stabilization of composites with higher molecular weight can lead to higher SOC stocks (SAIDY et al., 2012). The oxide's capacity to stabilize SOC in soils is not yet simulated by most ecosystem models (e.g. Century and Roth-C) (GONÇALVES et al., 2017; LEITE and MENDONÇA, 2003), which may help to explain the high SOC stocks of the farm between 2001-2007 (Figure 3.5).

Along with the SOC stocks, crop yields also increased over time (Figures 3.5 and 3.6). Our results are consistent with the findings of many other studies (BHARDWAJ et al., 2011; DJIGAL et al., 2012; KUHN et al., 2016), where authors attribute their results to multiple factors including N availability and biological diversity. Although the relationship between SOC and crop yield cannot be analyzed as cause and consequence but as a coevolution process, the correlation between SOC and CEC (Table 3.3) indicates that the high SOC stocks helps to maintain soil nutrient availability. Some studies report negative effects of no-till on crop yield, but they are usually associated with the low soil temperatures in temperate climates (OGLE et al., 2012; PITTELKOW et al., 2014). In tropical and sub-tropical ecosystems, the nutrient (BHARDWAJ et al., 2011) and water (DEXTER, 2004) availability to crops are indirectly affected by SOC which positively influences crop yields.

The increase in SOC stocks is directly associated with the quantity, quality and frequency of added biomass-C (Figure 3.4). Our data shows that the absence of tillage alone does not guarantee an efficient system, but it has to be complemented with fertilization and crop rotation management. Thus, the biomass – C – SOC conversion rate simulated by Century, 16.47% (Table 4), and reported in other studies Ferreira et al. (2012), 14.1%, Cotrufo et al. (2015), 19%, can be achieved. With the maintenance of high C conversion rates, the new equilibrium state of the SOC stocks can be higher than under native vegetation (Figure 3.4). Studies have reported 116% higher SOC stocks in sub-tropical croplands in comparison to native vegetation (FERREIRA et al., 2016). This indicates that soil's capacity to sustain crop production can be increased along with the development of higher C input systems (TIVET et al., 2013).

In our knowledge, this is the first study which reported adoption of best management practices in sub-tropical systems. The increase of 1.55 ± 0.3 Tg in global grain production (Table 3.5) can help to close crop yield gaps in sub-tropical regions that are supposed to be around 60% of the total potential and have a big C debit for land use change (FOLEY et al., 2011). Our results can be more important for South Asian regions with higher expected population growth in future (Figure 3.3).

The amount of croplands in which the result was expanded (86 million ha) correspond to 6% of world croplands (FOLEY et al., 2011). On the other hand, the estimated amount of SOC down to 1 m depth (11.2 Pg C) correspond to 7 to 9% of the estimated for world croplands (CARTER and SCHOLES, 2000; STOCKMANN et al., 2013; UMWELTVERÄNDERUNGEN, 2009). These numbers highlight the potential of best management practices adoption and SOC sequestration in sub-tropical climates since these soils are considered of low C content.

Major sources of uncertainties in this study comprise the data variability and the model structure. The uncertainty in data input was reported as ±1 standard deviations and showed averages of 19.4% for crop yields and 19.6% for observed SOC stocks. The model structure's contribution was small 0.2 – 0.5%, compounding to a total of 20%. Other possible sources of uncertainties that were not accounted could be from maps accuracy, the effect of atmospheric CO_2 increase on SOC stocks and scaling up of best management practices.

The effect of increased atmospheric CO_2 concentrations on SOC stocks is still unclear due to several knowledge gaps like the impact of carbon climate feedback on SOC stocks (CHEN et al., 2012; FANG, 2005; PACHAURI et al., 2014; REICHSTEIN, 2005). Applying the equation described by Rustad (2001) to Paiquerê farm and Latitude module as a predictor, we found that soil respiration, N mineralization and plant productivity will increase by 0.8%, 1.06%, and 0.06% respectively, resulting in a net loss of SOC. However, applying findings of other studies about the impact of increased CO_2 concentration on net primary production (ABEBE et al., 2016; AINSWORTH et al., 2002; HAN et al., 2015; HAO et al., 2014; LI et al., 2013; MENG et al., 2014; O'LEARY et al., 2015; WANG et al., 2013), we found annual biomass-C input of 15.73 and 26.17 Mg ha^{-1} for wheat/soybean and maize/oat crop rotation respectively. This will result in an increase of 6 Mg C ha^{-1} in 10 years leading to a net gain of

SOC. Future studies aiming to address these knowledge gaps may lead to better estimates of its net effect.

Despite the uncertainties related to the effect of elevated CO_2 and best management practices expansion, our results showed that best management practices are a powerful tool to increase crop yield and sequester C in soils. However, it should be adopted as an integrated system, along with good fertility management and high biomass-C input. The findings of our study can serve as a model for efforts aiming to improve no-till farming systems and its capacity to estimate the global impact of conservation agriculture.

3.5 CONCLUSIONS

Both crop yield and SOC stocks increased over time in Paiquerê farm and the models provide similar simulations for SOC dynamics. However, the stocks were higher and closer to the observed values for Century compared to Roth-C. The expansion of the results showed that best management practices has the potential to sequester 5.4±0.02 to 6.3±0.02 Pg C in 60 years (0-20 cm depth) considering current and 15% increase in biomass C input. However, considering 0-100 cm depth, to storage can be up to 9.6±3 to 11.2±3 Pg C considering current and 15% increase in biomass-C input, which is equivalent to a sequestration of 34.6±11 to 40.5±11 Pg CO_2 in 60 years. This is equivalent to 7 to 9% of the world SOC stocks in 6% of the world croplands (86 million ha) and correspond to 11 years of global land use and land use change emissions, indicating that best management practices are a powerful tool to promote C sequestration in sub-tropical soils.

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GENERAL CONCLUSION

We showed that land use and land use change was a major source of greenhouse gas emissions (376.2±130 Tg C) in the Campos Gerais region, especially before 1985, after fossil fuel combustion highlighted as the major source. Conservative best management practices are a powerful tool for mitigate greenhouse gas emissions in sub-tropical systems. The historical contribution of no-till -30.4 ± 23.9 Tg C or 0.5 Tg C Mha^{-1} $year^{-1}$ and future perspectives with adoption of best management practices in the region 42 Tg C or 15 Mg C ha^{-1} in 100 years and globally were suitable -5.4 ± 0.02 in 60 years corroborate these results.

The mitigation potential of the system in Campos Gerais region is equivalent to 13 years of total emissions and 105 years of agriculture, forestry and other land use sector emissions, making the sector C balance neutral for the next 100 years. However, the study also highlight the importance of high intensity crop rotation for keep the soil carbon stocks, since a reduction of 30% in crop residue input resulted in emissions of 15 Mg C ha^{-1} in 60 years with negative impacts for soil fertility. These results highlight the importance of public policies aiming to subside the adoption of conservative practices as “ABC program” since this sector can be very important for Brazil to reach its goals of reduce greenhouse gas emissions by 43% in 2030.

In our knowledge, this study is the first that produced a greenhouse gases inventory, calibrated and applied the models Century and Roth-C for Paraná State. Other soil carbon models as DAISY, CANDY, DayCent, DNDC, and Earth System models as CESM (CLM) have to be tested for reduce the findings uncertainty. The same way the historical lack of data uncertainty can be reduced with backward simulations. Adoption of periodic data collection and environmental monitoring stations can reduce the uncertainties in the future. Our methodology, organization of available database and model simulations for test different scenarios can be used to divulge the potential of conservation agriculture to mitigate greenhouse gas emissions and promote carbon sequestration in soils.

ANEXOS

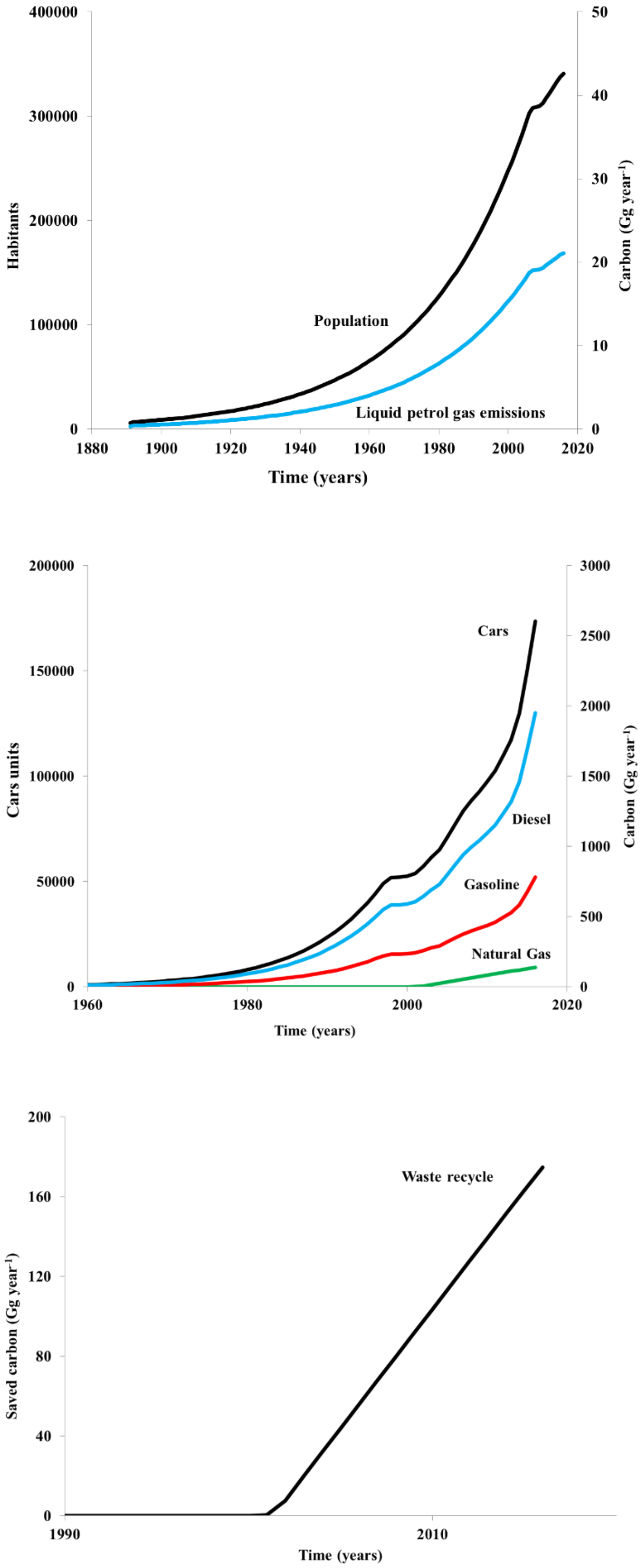

Figure 4.1: Historic population growth, fossil fuel emissions and waste recycle in Campos Gerais region.

Table 4.1: Coefficients of greenhouse gas sources, CO2 equivalent conversion factors and reference carbon stocks used for the inventory calculations.

Greenhouse gas source	**Carbon stock**	**Coefficient/Consequence**	**Reference**
	Soil (0-20 cm) Grassland	94.9 Mg ha^{-1}	Sá et al. (2014)
	Soil (0-20 cm) Forest	165.3 Mg ha^{-1}	Hartmann et al. (2014)
	Soil (0-20 cm) Cerrado	61.6 Mg ha^{-1}	Mello et al. (2014)
	Soil (0-20 cm) Wetland	123.4 Mg ha^{-1}	Gonçalves et al. (2015)
	Aboveground Grassland	2.4 Mg ha^{-1}	De Castro and Kauffman (1997)
	Aboveground Forest	89 Mg ha^{-1}	Watzlavick et al. (2012)
	Aboveground Cerrado	13.6 Mg ha^{-1}	De Castro and Kauffman (1997)
	Aboveground Wetland	1.9 Mg ha^{-1}	Pozer and Nogueira (2004)
	Belowground Grassland	2.1 Mg ha^{-1}	Pillar et al. (2009)
	Belowground Forest	6.3 Mg ha^{-1}	Watzlavick et al. (2012)
	Belowground Cerrado	12.2 Mg ha^{-1}	Abdala et al. (1998)
	Belowground Wetland	1.7 Mg ha^{-1}	Pillar et al. (2009)
Conversion Forest to Pasture		Loss of vegetation carbon	Assumption
Conversion Grassland to Pasture		-	Assumption
Conversion Cerrado to Pasture		Loss of vegetation carbon and change in SOC	Assumption
Conversion Wetland to Pasture		Loss of vegetation carbon and change in SOC	Assumption
Conversion Pasture to Planted forest		Loss of vegetation carbon	Assumption
Conversion Pasture to Agriculture		Loss of vegetation carbon and 0.69 of SOC	IPCC (2014)
	Aboveground planted forests	42.62 Mg ha^{-1}	Cerri et al. (2010)
	Aboveground agriculture	2.6 Mg ha^{-1}	Sá et al. (2008)
	Belowground planted forests	42.62 Mg ha^{-1}	Cerri et al. (2010)
	Belowground agriculture	1 Mg ha^{-1}	Sá et al. (2008)
Rate of SOC increase in forests		0.34 Mg ha^{-1} year^{-1}	Cerri et al. (2010)
Rate of SOC decrease in agriculture CT		- 1.6 Mg ha^{-1} year^{-1}	Sá et al. (2014)
Rate of SOC increase in agriculture NT		0.6 Mg ha^{-1} year^{-1}	Sá et al. (2017), Zanatta et al. (2007)
Emission from drained wetlands		Difference from grasslands	Sá et al. (2014), Gonçalves et al. (2015)
Emission from livestock management enteric fermentation		0.33 Mg C year^{-1} head^{-1}	Cerri et al. (2010)
Emission from livestock management manure management		0.05 Mg C year $^{-1}$ head^{-1}	Cerri et al. (2010)

Emission from farm activities conventional tillage		35.3 Kg EC ha^{-1}	Lal (2004)
Emission from farm activities no-till		5.8 Kg EC ha^{-1}	Lal (2004)
Emission from forest activities (nitrogen fertilization + fossil fuel)		0.02 Mg ha^{-1} year^{-1}	Cerri et al. (2010)
Lightning kerosene		21.5 pounds CO_2 Gallon^{-1}	EIA (2017)
Liquid petrol gas		13.7 pounds CO_2 Gallon^{-1}	EIA (2017)
Natural gas		53.12 Kg CO_2 feet^{-3}	EIA (2017)
Gasoline		19.64 pounds CO_2 Gallon^{-1}	EIA (2017)
Diesel		22.38 pounds CO_2 Gallon^{-1}	EIA (2017)
Airplane gasoline		18.4 pounds CO_2 Gallon^{-1}	EIA (2017)
Waste recycle		- 3.15 Mg CO_2 Mg^{-1}	EIA (2017)
	Paiquere NT aboveground biomass	4.5 Mg C ha^{-1}	Gonçalves et al. (2015)
	Paiquere NT belowground biomass	1.8 Mg C ha^{-1}	Gonçalves et al. (2015)
	Paiquere NT SOC increase rate	Century model	-
Emission from pasture (Machinery sowing + harvensting)		0.01 Mg C ha^{-1}	Cardoso et al. (2003)
Emission from pasture - Machinery nitrogen fertilization (Truck + Nitrogen)		0.13 Mg C ha^{-1}	Cardoso et al. (2003)
Rate of pasture SOC increase		0.48 Mg C ha^{-1}	Cardoso et al. (2003)
C		3.6 CO_2	EIA (2017)
CH_4		25 CO_2	EIA (2017)
N_2O		298 CO_2	EIA (2017)
CO_2		1 CO_2	EIA (2017)

* CT = Conventional tillage with soil plough, EQ = Equivalent carbon, NT = No-till, SOC = Soil organic carbon.