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Soil carbon inventory to quantify the impact of land use change to mitigate greenhouse gas emissions and ecosystem services☆

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A B S T R A C T

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 emissions. The objectives of this study were to quantify (1) the impact of LULUC on greenhouse gas (GHG) emissions in a subtropical region and (2) the role of conservation agriculture to mitigate GHG emissions promoting ecosystem services. We developed a detailed IPCC Tier 2 GHG inventory for the Campos Gerais region of southern Brazil that has large cropland 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 conservation best management practices, to all croplands in the region from 2017 to 2117. Our results showed historical (1930–2017) GHG emissions of 412 Tg C, in which LULUC contributes 91% (376 ± 130 Tg C), the uncertainties ranged 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 52 ± 24 Tg C in 0.6 Mha in a period of 47 years (1.8 Tg C Mha^{-1} year^{-1}) and no-till sequestered 30.4 ± 24 Tg C in 2 Mha in a period of 32 years (0.5 Tg C Mha^{-1} year^{-1}) being the principal GHG mitigating activities in the study area. 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 carbon (C) sink and promoting ecosystem services.
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1. Introduction

Currently, major sources 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). The LULUC sector 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

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.

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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).

GHG 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 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 soil organic carbon (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 hole 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 (0.3–0.4 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 (0.08–0.28 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). In this approach, it 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 one of the major issues obstructing the development of GHG markets (Gren and Aklilu, 2016). In 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 SOC 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 subtropical region during its development, highlighting the effect of land use change (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 “conservation best management practices” and characterized by high crop yields and crop rotation intensity (Gonçalves et al., 2017a,b). We used the Century model to simulate the adoption of conservation best management practices in entire croplands of the region.

2. Materials and methods

2.1. Study area

We conducted this study in Campos Gerais region, located in Paraná state, Southern region of Brazil (Fig. 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).

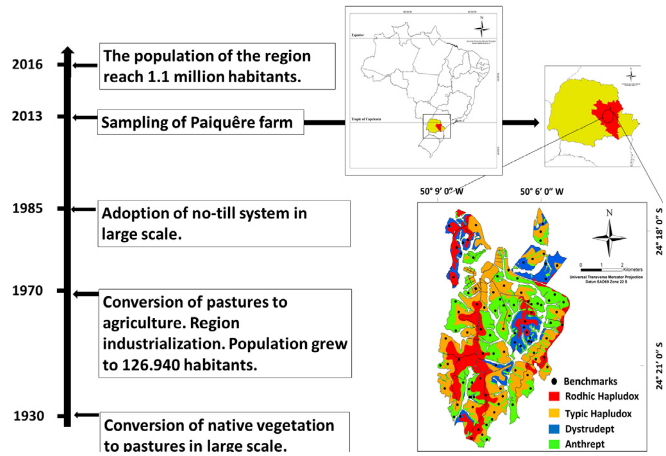

Fig. 1. Localization of Brazil, Paraná state and Campos Gerais region, and main events occurred in Campos Gerais region, Paiquerê farm, soil types and benchmark locals.

The altitude ranges between 700 and 1290 m (Melo et al., 2007) and the climate is classified as subtropical 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. *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 (Fig. 1). 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).

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.

2.3. *Farming system site and conservation 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 (Fig. 1) and managed for 30 years under continuous conservation best management practices. In this study, conservation best management practices meansagricultural best management practices that meet current and future societal needs for food, fiber, and 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 (Tilman et al., 2002). 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 rainwater. The average crop yield for the period of 2001–2013 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,b). 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,b). 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.

2.4. *Greenhouse gas 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 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.

$$CG\ GHG_{em} = LULUC_{em} + Fossil\ fuel_{em} + Others_{em} \tag{1}$$

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, 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., 2014, 2017) 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).

$$LULUC_{em} = LUC_{em} + LU_{em} \tag{2}$$

$$LUC_{em} = \text{Vegetation slash and burn}_{em} + \text{Wetland draining}_{em} + SOC_{em} \quad (3)$$

$$LU_{em} = \text{Soil tillage } SOC_{em} \text{ - No-till } SOC_{seq} \text{ - Vegetation growth}_{seq} + \text{Farm and forestry}_{em} + \text{Livestock}_{em} \quad (4)$$

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)).

$$\text{Fossil Fuel}_{em} = \text{Household}_{em} + \text{Transport}_{em} + \text{Industrial}_{em} \quad (5)$$

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

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

$$\text{Industrial}_{em} = \text{Natural gas}_{em} \quad (8)$$

$$\text{Others}_{em} = \text{Waste recycle}_{seq} \quad (9)$$

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)).

$$\text{Ecosystem C stocks} = \text{Aboveground biomass C} + \text{Belowground biomass C} + \text{SOC} \quad (10)$$

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,b), 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 various sources as described in the Tables 1–3.

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 EIA (2017). 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 (Fig. 1). 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)).

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

In 2013, we defined 98 locations as benchmarks (Fig. 1) comprising all soil types and texture gradients of the farm (Gonçalves et al., 2017a). We collected bulk soil samples with an auger and 5 × 5 cm core rings from two depth intervals, 0–10 and 10–20 cm. We considered the 0–20 cm layer because this is the depth simulated by Century models. In addition, despite the importance of sub-soil C, most of the available data regarding SOC stocks for South Brazil (Pillar et al., 2009; Sá et al., 2014, etc) was from 0 to 20 cm depth interval, so the consideration of deeper soil layers would add uncertainty to the inventory. 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).

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

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. (2017)a,b.

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 for obtain the new SOC stocks. We simulated the SOC stocks in periods of 50 years (2017–2067, 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 not simulate the future development of the region or to test SOC emission feedbacks with climate changes projections (CMIP5, https://cmip.llnl.gov/cmip5/) but analyze how much C can be saved with the adoption of conservation 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,b).

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

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 10000 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 10000 times (Eq. (15)).

$$\text{Estimated SOC}_{(1|10000)} = \beta_0 + \beta_1{}^*\text{Sim var. }1_{(1|10000)} + \beta_2{}^*\text{ Sim var. }2_{(1|10000)} + \beta_3{}^*\text{ Sim var. }3_{(1|10000)} + \beta_4{}^*\text{ Sim var. }4_{(1|10000)} + \beta_5{}^*\text{ Sim var. }5_{(1|10000)} \tag{15}$$

v) The 95% confidence intervals were generated using the 10000 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 (10000). For the uncertainties calculation we used the software R v. 3.4.0 (R Core team, 2017).

3. Results

3.1. Native vegetation in Campos Gerais region

The Campos Gerais region has a total land surface area of 3.2 million ha (Table 1). Out of this land area, 65% has forests, 31% has grasslands, 3% has wetlands and 1% has Brazilian acid savannas, the Cerrados (Fig. 2). 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 accounted for 83% of C (554.4 ± 117.6 Tg), grasslands for 15% C (100 ± 23.4 Tg), wetlands accounted for 1.6% C (10.8 ± 2.1 Tg) and the Cerrados accounted for 0.4% C (2.8 ± 0.7 Tg).

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). 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 and by 1970s the C in the native vegetation was reduced to 4.4% (29.2 ± 0.6 Tg) of the original total carbon stocks, (Table 2).

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 increase in agricultural land area reduced the total amount of C in the region to 278 Tg. 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, calculated summing the new C stocks of each land use system.

Between 1970 and 1984, the soil carbon stocks increased in planted forest lands to 118 Mg ha^{-1} due to the high C input trough leaves and branches. On the other hand, SOC in agriculture land decreased to 40.5 Mg ha^{-1} due to the soil tillage (Table 2). The C stocks in the vegetation of planted *Pinus* sp. *L.* and *Eucalyptus* sp. *L'Her* forests contributed to increase total C stocks to 270 Tg.

During 1985s, the conversion of agriculture land cultivated with soil tillage to no-till system started, 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 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 (Fig. 4), 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 a period of 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 a period of 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 1930–1970, 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 1985–2017 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}).

Table 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)	$94.9_{\pm 23.3}$	$165.3_{\pm 27.2}$	$61.6_{\pm 21.5}$	$123.4_{\pm 24.9}$	
	Aboveground biomass	$2.4_{\pm 0.3}$	$89.0_{\pm 48.0}$	$13.6_{\pm 5.3}$	$1.9_{\pm 0.7}$	
	Belowground biomass	$2.1_{\pm 0.6}$	$6.3_{\pm 4.5}$	$12.2_{\pm 8.8}$	$1.7_{\pm 0.6}$	
	Total	$99.4_{\pm 23.3}$	$260.6_{\pm 55.3}$	$87.4_{\pm 23.8}$	$127.0_{\pm 24.9}$	
Carbon (Tg)	Soil (0–20 cm)	$95.5_{\pm 23.4}$	$351.7_{\pm 57.9}$	$1.9_{\pm 0.7}$	$10.5_{\pm 2.1}$	$459.6_{\pm 62.5}$
	Aboveground biomass	$2.4_{\pm 0.3}$	$189.3_{\pm 102.1}$	$0.4_{\pm 0.2}$	$0.2_{\pm 0.06}$	$192.3_{\pm 102.1}$
	Belowground biomass	$2.1_{\pm 0.6}$	$13.4_{\pm 9.6}$	$0.4_{\pm 0.3}$	$0.1_{\pm 0.05}$	$16.0_{\pm 9.6}$
	Total	$100.0_{\pm 23.4}$	$554.4_{\pm 117.6}$	$2.8_{\pm 0.7}$	$10.8_{\pm 2.1}$	$668.0_{\pm 120.0}$

*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 Goncalves et al. (2017).

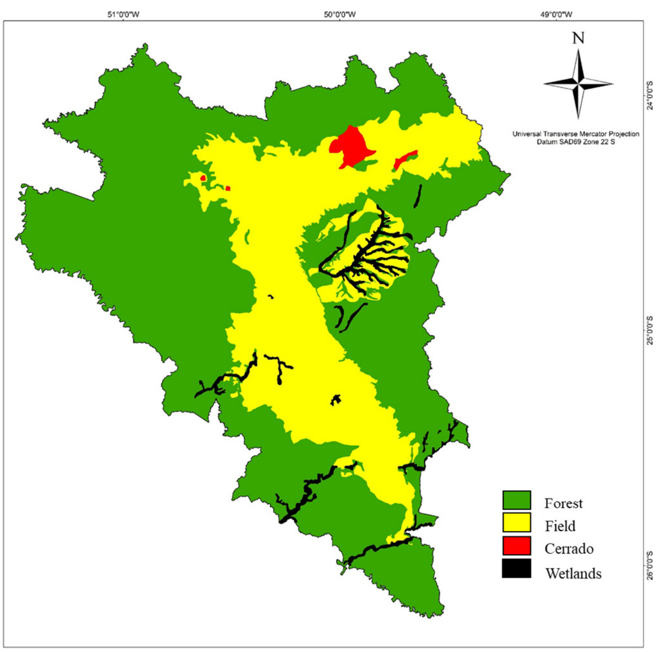

Fig. 2. Native vegetation in Campos Gerais region.

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} (Fig. 5). 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 (1930–1970) GHG emission trend, in which LULUC had the biggest contribution to GHG emissions.

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 conservation 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 (Fig. 6, Table 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 (Fig. 4). 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 (Fig. 5).

4. Discussion

4.1. Native vegetation, land use change and historical emissions

Patterns of natural vegetation in the Campos Gerais region described in this study (Table 1, Fig. 2) 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, Fig. 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 (Fig. 4). Out of this, LUC accounted for 356.5 Tg C and the biggest LUC occurred during 1930s emitted 297.3 Tg of C (Tables 1 and 2).

Conversion of pasture to agriculture land in 1970s emitted 62.9 Tg of C (Table 2, Fig. 3). Other studies from the same region (de Moraes 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

Table 2
Historical land use change in Campos Gerais region.

Year	Carbon stock (Mg ha^{-1})	Area (ha)	Land use				
			NV		Economic activities		
			Forest	Wetlands	Pasture		
			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)		$28.1_{\pm 6.0}$	$1.1_{\pm 0.2}$	$311.5_{\pm 73.0}$		
			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.

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, Fig. 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). In the other hand, many 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 is considered a potential source of GHG emissions (Joshua et al., 2017). 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), 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 subtropical 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 subtropical agro ecosystems (Gonçalves et al., 2017a,b; Lal, 2001).

The described pathway of GHG emissions is expected to occur in other subtropical 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.

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} (Fig. 5). 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. In addition, recent studies reported the acid wetlands from Paraná state to have small population of methane producing bacteria and archaea, suggesting the methane emissions from the region wetlands can be small (Etto et al., 2012, 2014).

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% (Fig. 5). 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

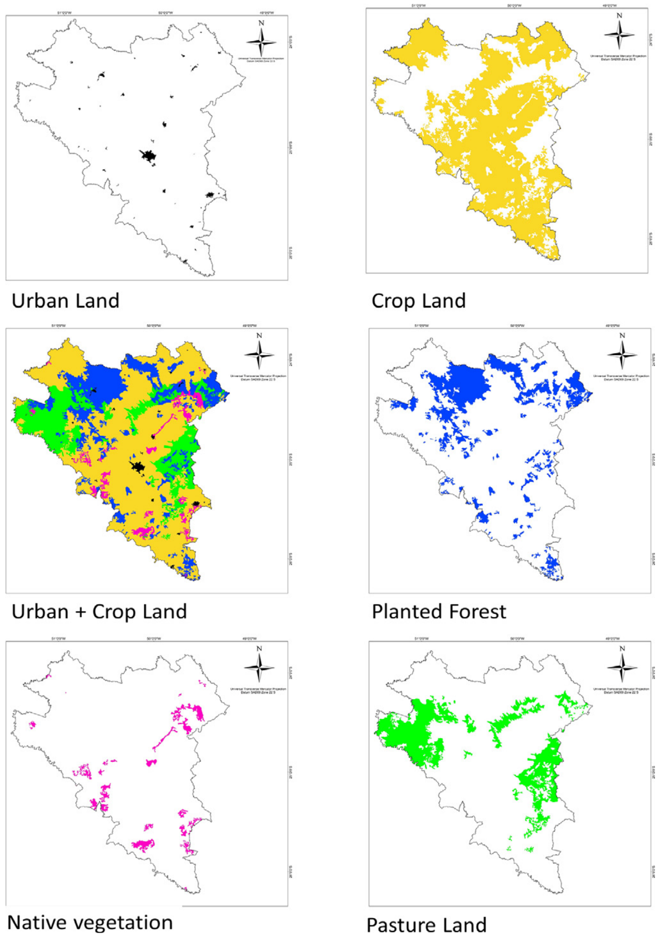

Fig. 3. Land use in Campos Gerais region.

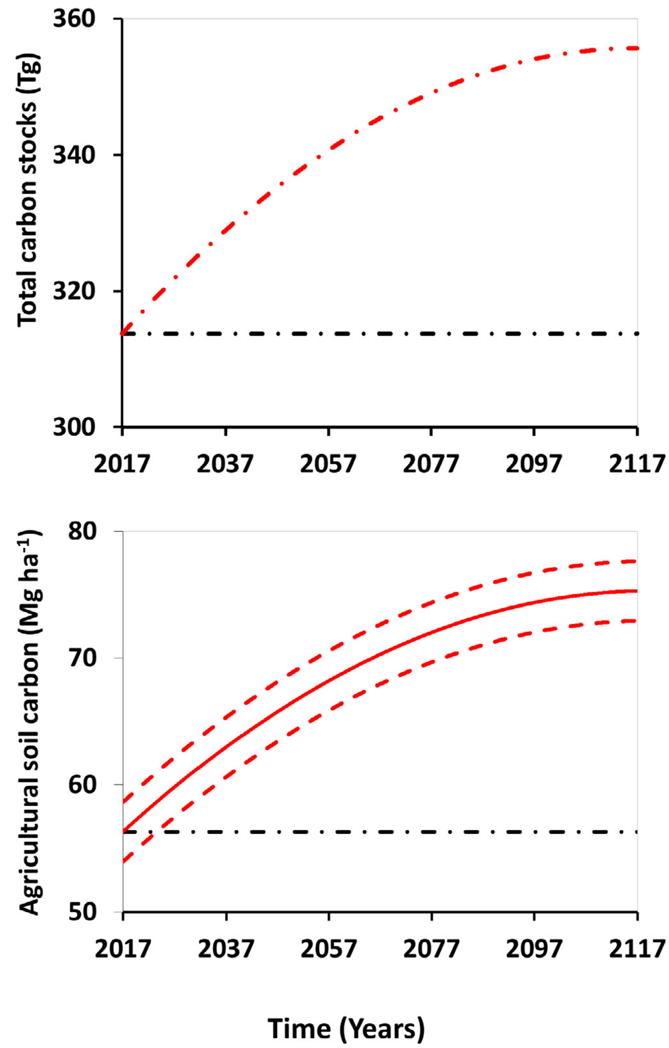

Fig. 4. Historic greenhouse gases emissions: a) Ecosystem carbon stocks, emission from land use change and mitigation from LULUC sector; b) Historic emissions from land use and fossil fuel; c) Emissions from fossil fuel sector and waste recycle.

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 (Fig. 5). 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 represents about 83% of total emissions and agriculture plus waste 17% (Su et al., 2016). This shows that regions currently emitting GHG 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 (Fig. 5). Agriculture and planted forests emissions are low, accounting for just 2.7% or 0.01 Tg C year^{-1} (Fig. 5), and GHG mitigation by soil and trees C sequestration was 1.37 Tg C year^{-1} between 1985 and 2017 (Table 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 USA that have more than 600 million cattle heads or 40% of the world flock (FAO, 2015). However, the intensification of livestock production systems may

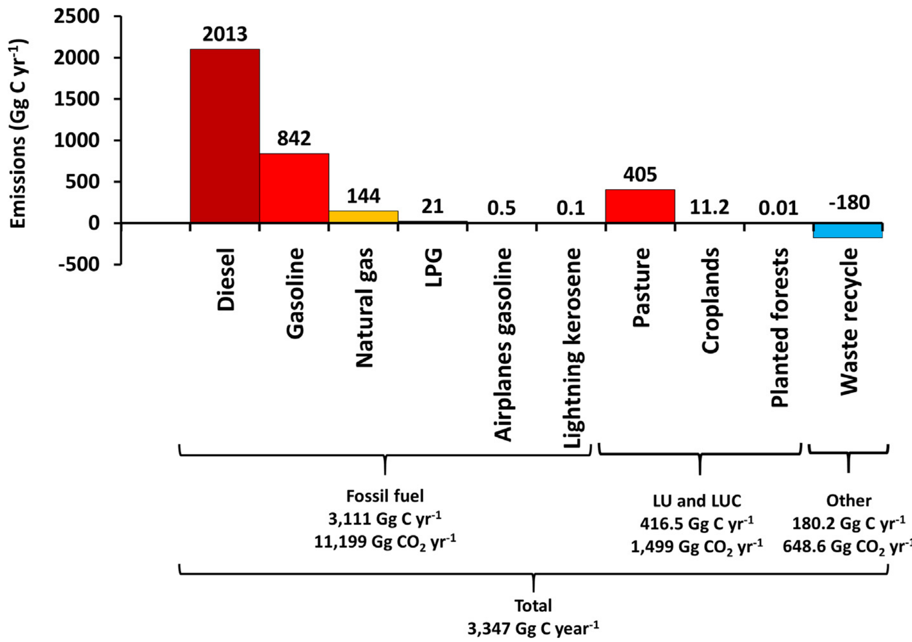

Fig. 5. Annual greenhouse gases emissions in Campos Gerais region.

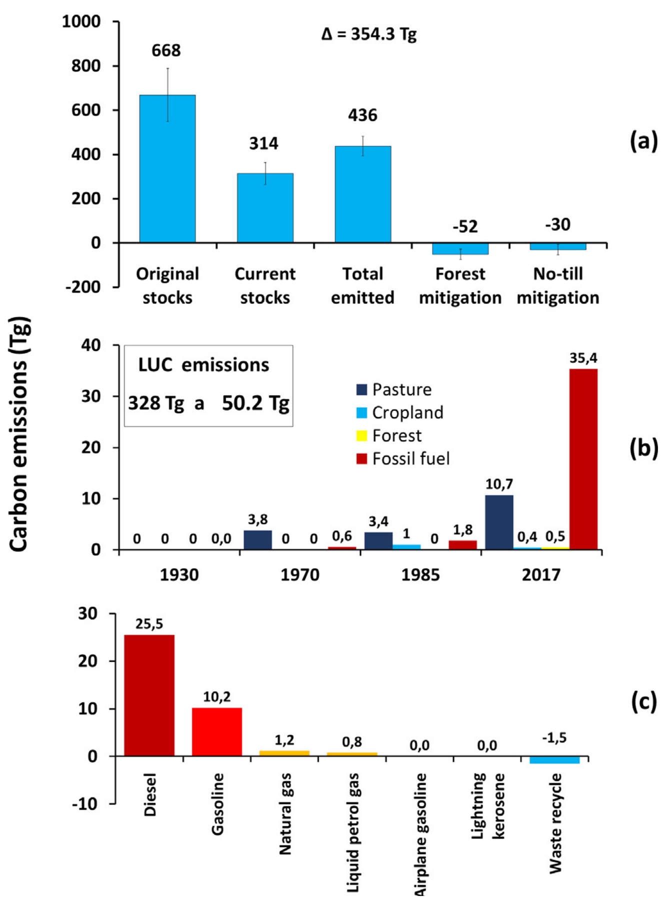

Fig. 6. Future agriculture soil carbon stocks and total carbon stocks in Campos Gerais region considering the adoption of high quality no-till system. The black line refers to no adoption of high quality no-till, and the red refers to adoption in 2017. The dashed lines refer to 95% confidence intervals for the predicted values.

lead to GHG mitigation since it can reduce deforestation, activity that is the major source of GHG emission (Table 2) especially in Amazon region (da Silva et al., 2017).

4.3. Future scenarios and carbon offset

Our results suggest that adoption of conservation best management practices can mitigate 42 Tg C until 2117 (Table 3, Fig. 6) making AFOLU sector a net C sink. This indicates that conservation agriculture is a power full 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 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 CG 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 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 founded that the 0–20 cm depth have just 56% of SOC content (Gonçalves et al., 2015), in this way the total SOC stocks can be up to 100.5, 125.5, 134.5 Mg ha^{-1}, with 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 subtropical and tropical climates showed higher yields between 20 and 70% in no-till systems in comparison to soil tillage management (Bhardwaj et al., 2011; de Moraes 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 subtropical 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

Table 3
Future scenarios with high quality no-till system adoption in Campos Gerais region.

Year	Carbon ($Mg\ ha^{-1}$)	Area (ha)	Native vegetation		Economic activities		
			Forest	Wetlands	Pasture	Planted forests	Agriculture
			107.809	8.310	622.915	583.032	1.928.146
2017	Soil (0–20 cm)		$165.3_{\pm 27.2}$	$123.4_{\pm 24.9}$	$94.9_{\pm 23.3}$	$140.9_{\pm 23.3}$	$56.3^{§}_{\pm 23.3}$
2017	Aboveground biomass		$89.0_{\pm 48.0}$	$1.9_{\pm 0.7}$	$2.4_{\pm 0.3}$	$42.62^{£}_{\pm 6.0}$	$2.6_{\pm 0.35}$
2017	Belowground biomass		$6.3_{\pm 4.5}$	$1.7_{\pm 0.6}$	$2.1_{\pm 0.6}$	–	$1.0_{\pm 0.1}$
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)		$28.1_{\pm 6.0}$	$1.1_{\pm 0.2}$	$61.9_{\pm 14.5}$	$107.0_{\pm 13.9}$	$115.6\ _{\pm 44.9}$
2018–2067	Soil (0–20 cm)		$165.3_{\pm 27.2}$	$123.4_{\pm 24.9}$	$94.9_{\pm 23.3}$	$140.9_{\pm 23.3}$	$70.3_{\pm 26.1}\ ^{\pm 2.3€}$
2018–2067	Aboveground biomass		$89.0_{\pm 48.0}$	$1.9_{\pm 0.7}$	$2.4_{\pm 0.3}$	$42.62^{£}_{\pm 6.0}$	$4.5_{\pm 0.6}$
2018–2067	Belowground biomass		$6.3_{\pm 4.5}$	$1.7_{\pm 0.6}$	$2.1_{\pm 0.6}$	–	$1.8_{\pm 0.3}$
2018–2067	Total		$260.6_{\pm 55.3}$	$127.0_{\pm 24.9}$	$99.4_{\pm 23.3}$	$183.5_{\pm 23.8}$	$76.7_{\pm 26.1}$
	Total carbon (Tg)		$28.1_{\pm 6.0}$	$1.1_{\pm 0.2}$	$61.9_{\pm 14.5}$	$107.0_{\pm 13.9}$	$147.9_{\pm 50.3}$
2068–2117	Soil (0–20 cm)		$165.3_{\pm 27.2}$	$123.4_{\pm 24.9}$	$94.9_{\pm 23.3}$	$140.9_{\pm 23.3}$	$75.3_{\pm 26.1}\ ^{\pm 2.3}$
2068–2117	Aboveground biomass		$89.0_{\pm 48.0}$	$1.9_{\pm 0.7}$	$2.4_{\pm 0.3}$	$42.62^{£}_{\pm 6.0}$	$4.5_{\pm 0.6}$
2068–2117	Belowground biomass		$6.3_{\pm 4.5}$	$1.7_{\pm 0.6}$	$2.1_{\pm 0.6}$	–	$1.8_{\pm 0.3}$
2068–2117	Total		$260.6_{\pm 55.3}$	$127.0_{\pm 24.9}$	$99.4_{\pm 23.3}$	$183.5_{\pm 23.8}$	$81.7_{\pm 26.1}$
	Total carbon (Tg)		$28.1_{\pm 6.0}$	$1.1_{\pm 0.2}$	$61.9_{\pm 14.5}$	$107.0_{\pm 13.9}$	$157.5_{\pm 50.3}$

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 conservation best management practices 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 conservation 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 conservation best management practices 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 $year^{-1}$, 5–15% global fossil fuel emissions and Sá et al. (2017) proposed that no-till system could sequester 2.01 Pg C between 2016 and 2050. Though the adoption of conservation 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 subtropical and tropical croplands.

4.4. Ecosystem services upon adoption of 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 knowledge 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 mean turnover time and soils potential to sequester C, are described as main knowledge gaps (Gren and Carlsson, 2013). Elofsson and Gren (2018) reported that accounting for SOC pool can reduce European carbon taxes from 50 to 33%. In addition to C price, environmental services have to be considered. Telles et al. (2011) estimated cost of soil erosion in Paraná state to be 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%.

4.5. Study approach and uncertainty analysis

Although the effect of LUC promoting vegetation slash and burn, reducing biomass input and breaking soil aggregates on GHG emissions is well known, 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 subtropical 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 subtropical soil have a high capacity to store C. Gonçalves et al. (2017)a,b attributed the high capacity of subtropical soils to store C to the high content of Fe and Al oxides, however the soil aggregation process may 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., 2006, 2007, 2010). 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 3, Fig. 6) of the total uncertainty. 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 and 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 and 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. The limited number of studies that look for C stocks in soil and vegetation in subtropical 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.

5. Conclusions

Our results showed that until 1985 most of the region GHG 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 conservation 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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