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ABSTRACT

Soils can be a source or sink of atmospheric CO_2, depending on the historic and existing land use and management. We used long term soil management database of a production farm that is based on principles of conservation agriculture such as: a) eliminate soil disturbance; b) maintain permanent soil surface cover; C) adopt crop diversity with high biomass-C input; for 30 years and agroecosystem models to study the potential of different management options to sequester C in soils. Using Century and Roth-C models we simulated the carbon stocks evolution in the farm and four subtropical soil management scenarios and studied C sequestration potential. The scenarios were: 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}). Our results demonstrate that soil organic carbon continuously increased after conservation management practices adoption in 1985 until 2015, and currently soil organic carbon 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} soil organic carbon stocks. The same way, crop yields increased with time, and were more pronounced for maize compared to soybean and wheat. The scaling up of model results to similar climate and soil types indicated that conservation management practices has the potential to sequester 2.7 ± 0.02 Pg C at 0–20 cm and 4.8 ± 3 Pg C at 0–100 cm soil depth in 43 million ha area globally. In the 30% and 15% decrease scenarios the sequestration were 2.2 ± 0.02 and 2.4 ± 0.02 Pg C at 0–20 cm an in 15% increase scenario it goes to 3.2 ± 0.02 Pg C. This equilibrium soil organic carbon stocks considering the currently adopted system are equivalent to 3.5–4.5% of the world SOC stocks in 3% of the world croplands and correspond to 6 years of global land use and land use change emissions, indicating that conservation management practices can lead the soil be a sink and a promising tool to promote C sequestration in subtropical soils.

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1. Introduction

Globally about 1.1 ± 0.5 Pg C yr^{-1} is emitted through land use and land use change (LULUC). Of this value, 1.41 ± 0.17 Pg C yr^{-1} is emitted in the tropics and the northern mid latitudes act as a sink sequestering of -0.28 ± 0.21 Pg C yr^{-1}. 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. 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.

Conservation practices increases soil organic carbon (SOC) stocks when accompanied by high biomass input (Diekow et al., 2005, Mishra et al., 2010, Nadeu et al., 2015, Sá et al., 2014, 2015). De Oliveira Ferreira et al. (2018) studied five conservative systems in southern Brazil and reported that SOC increases when the system is based on good fertilization management and high carbon input to the soil trough crop residues. Hok et al. (2018) studied four conservation management systems based in soybean, cassava and rice in Cambodia and reported that most intense crop rotation systems lead to higher C storage in soils. Tivet et al. (2013) studying conservation systems in southern and central Brazilian regions reported high SOC stocks associated with the high biomass C input treatments. In addition, most of the management system experiments are relatively recent with less than 30 years of adoption (Rasmussen et al., 1998). Also, the absence of production farming system under long-term conservation 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.

However, 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 conservation systems? And what will be the impact of adopting conservation systems at global scale at suitable locations?

We think that knowledge gaps associated with the temporal crop yields improvement and its role in C sequestration in soils, is one of the main constraint to adapt experimental results at larger scales. The use of ecosystem models allowed us to evaluate different management practices for soil carbon sequestration at different depth intervals, when applied at similar soil types and climatic conditions globally. 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 conservation management practices for last 30 years; (ii) simulate the historical (up to 2018) 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 model simulations with the farm database; (iv) scale up the results to similar subtropical agroecosystems globally using GIS.

2. Material and methods

2.1. Study area

This study was conducted at Paiquerê Farm, located at 24° S 20′ 20″ and 50° W 07′ 31″ (Fig. 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 conservation best management practices. This farming system was chosen as it represents conservation best management practices in the Campos Gerais region, following the 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. 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 (Frísia, 2015 - http://www.frisia.coop.br/pt-BR/cooperativa/Paginas/relatorio-anual.aspx; Castrolanda, 2014 - https://www.castrolanda.coop.br/img/relatorio_anual/19RA2016/RA2016.pdf). This study site represents

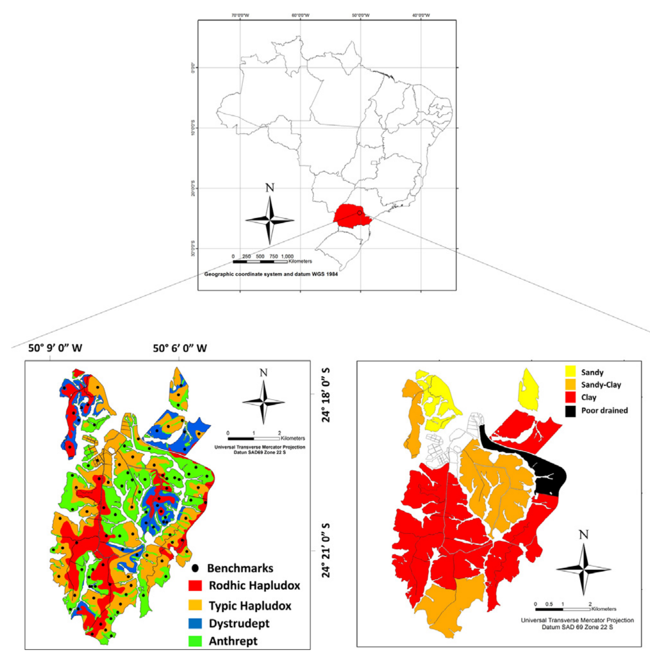

Fig. 1. Map with Paiquerê farm localization, soil types, sampling point and the soils grouped according to texture and drainage.

an example of a successful conservation best management practices farming system and is ideal to explore the potential of it to sequester C in soils.

The agricultural activities of this farm started in 1967 (Fig. 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 conservation 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 1), which provided the mean annual biomass input of 14.5 Mg ha^{-1} $year^{-1}$ (Table 1). The fertilization of the farm plots ranged from 180 to 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.

The predominant soil types (Fig. 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.

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 Mehlich-1 solution, soil P was determined by colorometry and K+ determined 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 2) was used to calculate SOC stocks using Eq (1).

$$SOC\ (Mg\ ha\text{-}1) = Bd * d * SOC * SA \quad (1)$$

Where: Bd = Bulk density in Mg m^{-3}, d = soil depth in m, SOC = soil organic carbon in Kg Kg^{-1} and SA = surface area in m ha^{-1}.

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 (Fig. 1). The sample collection followed the procedure (Gonçalves et al., 2017):

i) A total of 98 marked plots of 30 × 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 per depth; 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 °C and grinded to pass through a 2 mm sieve, and soil cores were oven-dried at 105 °C for 48–72 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).

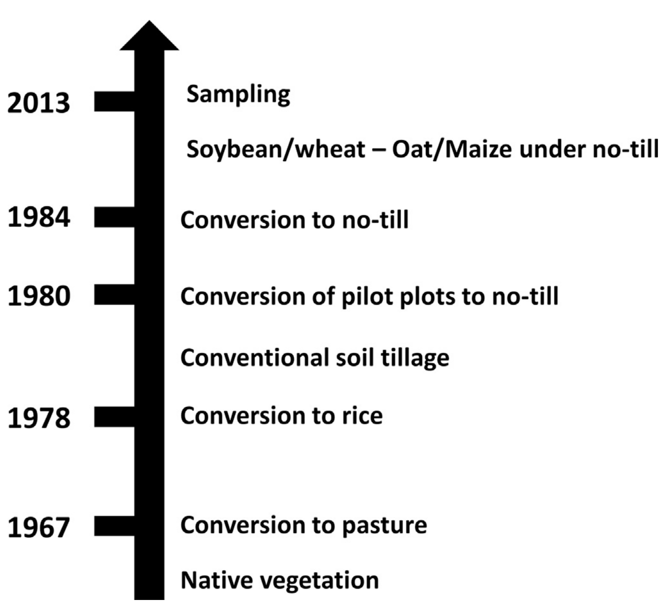

Fig. 2. Historic land use change in Paiquerê farm.

2.3. Century 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 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;

Table 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 culture that precede maize during the winter.

Table 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	$600_{\pm118}$	$300_{\pm122}$	$100_{\pm21}$	$1.09_{\pm0.03}$

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}.

2.4. Roth-C model initialization

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 (Fig. 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; Villarino et al., 2014), we assumed no changes in these indices over time, and used the crop yields from the farm's database (Table 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.

2.5. Soil organic carbon dynamics simulations

After the initialization, Century and Roth-C models were used to simulate the SOC pools dynamics in the farm from 1967 to 2015. The simulated pools were total, slow, active and passive soil carbon pools for Century, total, humine and microbial biomass soil 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 years periods, comprising 2015–2035, 2035–2055 and 2055–2075.

2.6. 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 to 2013 as yield maps using John Deere combines sensors with Greenstar 3 GPS integrated systems (Table 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.

2.7. 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 Sandy, Sandy-Clay and Clay groups and Poorly drained soils as result of shallow bedrock-soil limit in the GIS environment (Fig. 1, Table 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 (Fig. 5) to simulate SOC stocks in Paiquerê farm.

We used the results from Paiquerê Farm to expand for other continuous 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 (Fig. 3). We compared the crop yield gain with the current mean crop yield for the region obtained from the database of Rally da safra, 2017 - http://rallydasafra.com.br/). For the SOC stocks, we made the comparison with the current SOC stocks estimated for the same area (Fig. 3) using Vasques et al. (2018), 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 upscaling to 1 m, beyond Century

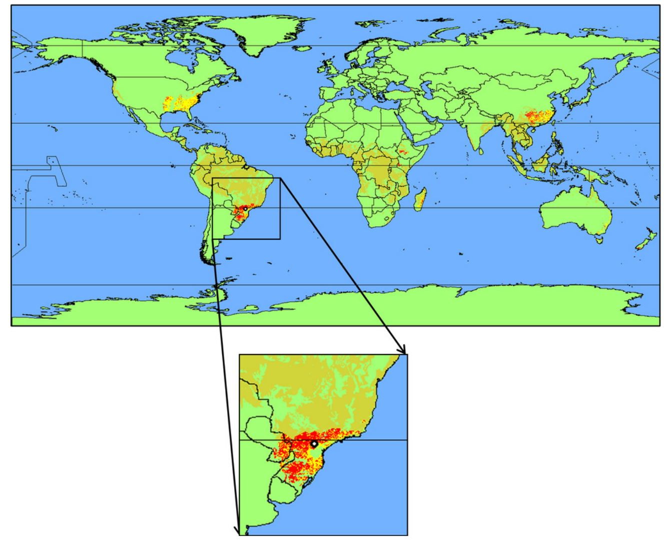

Fig. 3. Continuous croplands with similar climatic and soil characteristics of the farm. Yellow = Subtropical climate (Cf according to Köppen classification); Orange = Low activity clay soils (LCA according to Nachtergaele et al., 2008); Red = Croplands ≈ 43 million ha; White point in the circle = Location of Paiquerê farm.

simulations for 0–20 cm. For all the spatial analysis and scaling up we used the software ArcGIS v. 10.4.1 (ESRI, 2017).

2.8. 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 10000 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).

$$\mu \pm 1.96 * \sigma/\sqrt{n} \tag{2}$$

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 (10000). 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 Development Core Team, 2017) was used. A schematic representation of the methodology is show is Fig. 4.

3. Results

3.1. Soil organic carbon dynamics in Paiquerê farm

The Century model simulations estimated SOC stock of

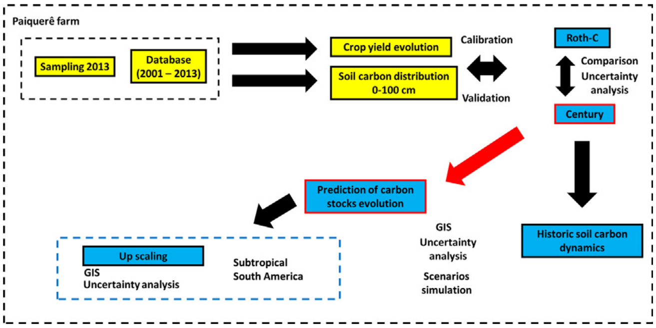

Fig. 4. Schematic methodology adopted in this study, the red squares and arrows indicate steps were just Century model was used. Yellow boxes = Data, Blue boxes = Models, No boxes text = Analysis, Red color indicates processes performed using Century model.

83 Mg ha^{-1} when the soil was under native vegetation (Fig. 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 with conservation best management practices 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 conservation management practices adoption the Century model indicated that SOC stocks reached a new equilibrium at 74 Mg ha^{-1}.

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 conservation best management practices adoption.

The Roth-C model showed similar SOC dynamics as predicted by the Century model, however the absolute values were underestimated (Fig. 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}. Conservation best management practices 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 conservation best management practices it increased and stabilized at 6.2 Mg ha^{-1}.

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} (Fig. 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}.

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, 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 showed a high affinity with CEC, demonstrating its importance to keep appropriate soil fertility levels.

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 (Fig. 5, Table 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

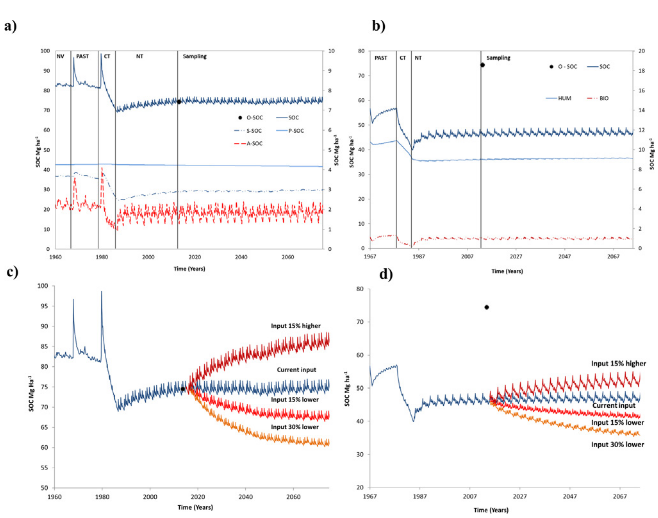

Fig. 5. Dynamics of total and SOC pools in Paiquerê farm accessed by Century **(a)** and Roth-C models **(b)**. Effect of residue C input increase and decrease assessed by Century **(c)** and Roth-C **(d)** in Paiquerê farm. *Plotted in **(a)** and **(b)** primary axis: SOC = Soil organic carbon; O-SOC = 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.

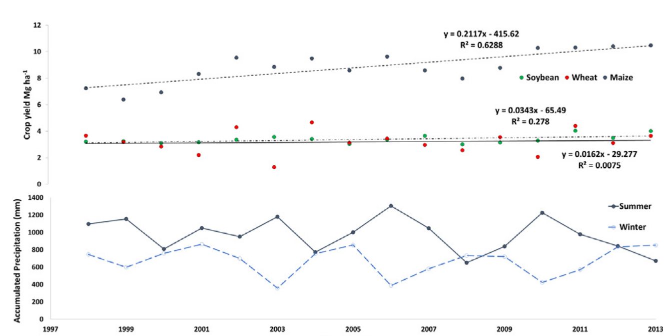

Fig. 6. Crop yield evolution and accumulated summer and winter precipitation between 1998 and 2013 in Paiquerê farm.

Table 3
Pearson correlation matrix with soil fertility attributes, precipitation and crop yield between 2001 and 2013.

	P	C	pH	Al	H + Al	Ca	Mg	K	BS	CECef
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		
CECef	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	CECef	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				
CECef	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**	**CECef**	**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				
CECef	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**	**CECef**	**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**				
CECef	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

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.

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 the first 40 years, then it decreased at 0.05 Mg ha^{-1} year^{-1} during the last 20 years.

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 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 sandy soil (23%), compared to sandy-clay (20%), clay (19%) and poorly drained soil (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 sandy (22%), compared to sandy-clay (18%), clay (15%) and poorly drained soils (15%).

The scaling of conservation management practices farming system to similar soil types and climatic conditions, shows a potential of 2.7 ± 0.02 Pg C sequestration in 60 years in soils to 0–20 cm depth (Table 5). With a 15% increase in biomass-C input this potential can increase to 3.2 ± 0.02 Pg C. These values are 1.1 ± 0.02 and 1.6 ± 0.02 Pg C greater compared to the current SOC estimates using Vasques et al. (2018) maps. This indicates a sequestration potential up to 4.0 ± 0.07 and 5.8 ± 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) (Fig. 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 4.8 ± 3 Pg C considering current biomass input, and 5.7 ± 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 17.3 ± 11 Pg CO_2 to 20.5 ± 11 Pg CO_2 in 60 years. This is equivalent to 5.5 years of global land use and land use change emissions (Pachauri et al., 2014). The Paiquerê farm yields are 28% (0.8), 18% (0.6) and 91% (5.0) Mg ha^{-1} higher for wheat, soybean and maize respectively compared to the current estimates for the region (Rally da safra, 2017 - http://rallydasafra.com.br/). This implies a total gain of 34.4 ± 25.8, 25.8 ± 8.6 and 215.0 ± 154.8 Tg of grains, when these results are scaled up globally.

4. Discussion

Both models indicated reduction in SOC stocks under soil tillage-based system and an increase and subsequent stabilization under conservation management practices. The Roth-C results were similar to Century model projections, however, the absolute SOC stock values were underestimated in Roth-C projections. 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 conservation management practices increased the SOC stocks, and the rate of increase during the first 2 decades

Table 4
Soil organic carbon stocks in all the soil groups of Paiquerê farm between 2015 and 2075.

Scenario	Soil group	Observed	2015			2035			2055			2075		
		SOC (2013)	SOC	Area	SOC	SOC	Area	SOC	SOC	Area	SOC	SOC	Area	SOC
		(Mg ha^{-1})	(Mg ha^{-1})	(ha)	(Gg)	(Mg ha^{-1})	(ha)	(Gg)	(Mg ha^{-1})	(ha)	(Gg)	(Mg ha^{-1})	(ha)	(Gg)
15% higher	Sandy		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
	Sandy-Clay		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
	Clay		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
	Poor drained		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
Upscaled area			62.94 ± 0.2	43.0 (Mha)	2.7 ± 0.02 (Pg)	70.39 ± 0.2	43.0	3.0 ± 0.02	72.59 ± 0.2	43.0	3.1 ± 0.02	73.76 ± 0.2	43.0	3.2 ± 0.02
Current	Sandy	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
	Sandy-Clay	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
	Clay	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
	Poor drained	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
Upscaled area			62.94 ± 0.2	43.0	2.7 ± 0.02	63.12 ± 0.2	43.0	2.7 ± 0.02	63.13 ± 0.2	43.0	2.7 ± 0.02	63.01 ± 0.2	43.0	2.7 ± 0.02
15% lower	Sandy		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
	Sandy-Clay		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
	Clay		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
	Poor drained		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
Upscaled area			62.94 ± 0.2	43.0	2.7 ± 0.02	58.40 ± 0.2	43.0	2.5 ± 0.02	56.80 ± 0.2	43.0	2.4 ± 0.02	56.24 ± 0.2	43.0	2.4 ± 0.02
30% lower	Sandy		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
	Sandy-Clay		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
	Clay		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
	Poor drained		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
Upscaled area			62.94 ± 0.2	43.0	2.7 ± 0.02	54.12 ± 0.2	43.0	2.3 ± 0.02	51.41 ± 0.2	43.0	2.2 ± 0.02	50.39 ± 0.2	43.0	2.2 ± 0.02

£ = 95% confidence interval.

Table 5
Expansion of the results to upscaled area.

	Crop yield (Mg ha^{-1})			Crop yield (Tg)				Reference
	Upscaled area	Paiquerê farm	Delta	Upscaled area	Paiquerê system	Delta		
Maize	5.5	$10.5_{\pm 3.6}$	$5.00_{\pm 3.6}$	236.5	$451.5_{\pm 154.8}$	$215.0_{\pm 154.8}$		Rally da Safra, (2017)
Soybean	3.4	$4.0_{\pm 0.2}$	$0.6_{\pm 0.2}$	146.2	$172.0_{\pm 8.6}$	$25.8_{\pm 8.6}$		Rally da Safra, (2017)
Wheat	2.8	$3.6_{\pm 0.6}$	$0.8_{\pm 0.6}$	120.4	$154.8_{\pm 25.8}$	$34.4_{\pm 25.8}$		Rally da Safra, (2017)
				SOC (Pg) Current	Paiquerê system (2075)	Delta	Delta (CO_2)	
Current				1.6	$2.7 \pm 0.02^{£}$	1.1 ± 0.02	4.0 ± 0.07	EMBRAPA (2018)
More 15% residue C				1.6	3.2 ± 0.02	1.6 ± 0.02	5.8 ± 0.07	EMBRAPA (2018)

*The expansion was done bases in a total upscale area of 43 million ha, corresponding to croplands in Cf climate (Köppen classification) and Low activity clay soils (IPCC, 2010) continuous to the studied farm.
*We used Brazilian soil carbon and crop yield means because it comprises about 90% of the entire upscaled area.
£ = 95% confidence interval.

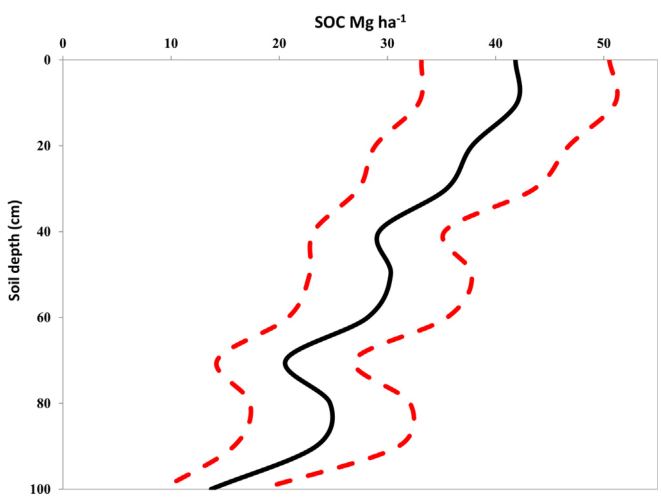

Fig. 7. Vertical distribution of the mean soil organic carbon stocks in Paiquerê farm. The red dot lines represent the standard deviations intervals.

(0.4 Mg ha^{-1} yr^{-1}) was similar to the values reported for medium term (20 years) experiments, 0.19 Mg ha^{-1} yr^{-1} to 0.55 Mg C ha^{-1} yr^{-1} (De Oliveira Ferreira et al., 2012; Zanatta et al., 2007). The SOC increased (Figs. 4 and 5) due to the high and constant biomass C input in the farm. The soybean/wheat crop rotation promoted input of organic material with different C/N proportions (Álvaro-Fuentes et al., 2012) and the oat/maize crop rotation where oat is a biomass crop with high C input, created an agroecosystem that can sustain C increase. It is important to note that high rates of SOC increase can be sustained with high plant biomass-C input, which further influences crop yields (Table 3, Fig. 6) and can be sustained by fertilization management. Some recent studies support our findings, for example De Oliveira Ferreira et al. (2018), studying long term no-till farming in Oxisols, reported that higher SOC stocks were associated with low Al^{3+} content and high exchangeable base saturations.

Although part of the carbon increase can be related to crop breeding (resulting in higher productivity and biomass production over time), conservation systems played a major hole in SOC sequestration and stocks increase. Sá et al. (2014), studying management systems for 30 years in the same region reported 20% higher SOC stocks in no-till system compared to conventional tillage system. The same way, Sá et al. (2001) compared different site managements and crop rotation systems, and reported 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 order to sustain plant production, fertilization can be the key to sustain SOC increase (Kirkby et al., 2013, 2014). Kirkby et al. (2013) reported that the fine SOC fraction follows the stoichiometry C:N:P:S = 10000:833:200:143, demonstrating that good fertilization management, as performed on the farm, is essential to promote and maintain higher SOC stocks. The fertilization management also influences the C stabilization processes. 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) showed medium correlation between SOC and Ca content. Although Al is important for C stabilization during organo-mineral complexations, in croplands with intense liming the Ca can substitute Al as the cationic bridge (Briedis et al., 2012; Inagaki et al., 2017, de Oliveira Ferreira et al., 2018).

Other factor that explains the high C stabilization in tropical and subtropical 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).

Along with the SOC stocks, crop yields also increased over time (Fig. 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 this 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) indicates that the high SOC stocks helps to maintain soil nutrient availability. Some studies report negative effects of no-till on crop yield, but these results are associated with the low soil temperatures in temperate climates (Ogle et al., 2012; Pittelkow et al., 2015). 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 (Fig. 4). The absence of tillage alone does not guarantee an efficient agroecosystem, but it has to be complemented with fertilization and crop rotation management. Thus, the biomass − C − SOC conversion rate simulated by Century, 16.5% (Table 4), and reported in other studies De Oliveira Ferreira et al. (2012), 14.1%, Cotrufo et al. (2015), 19%, can be achieved. Further, with the maintenance of high C conversion rates, the new equilibrium SOC stocks in farm lands can be higher in comparison to under native vegetation (Fig. 4). Studies have reported 116% higher SOC stocks in subtropical croplands in comparison to native vegetation (de Oliveira Ferreira et al., 2016). This indicates that soil's capacity to sequester SOC can be increased along with the development of higher C input cropping systems (Lal, 2004; Tivet et al., 2013).

In our knowledge, this is the first study which reported adoption of conservation management practices in subtropical systems. The increase of 275.2 ± 189.2 Tg in grain production (Table 5) can help to close crop yield gaps in the region 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 also be applied in South Asian regions, with similar soil types and climatic conditions where higher population growth is expected in future (Fig. 3).

The area of croplands in which the result was expanded (43 million ha) correspond to 3% of the 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 3.5–4.5% of the estimated for world croplands (Carter and Scholes, 2000; Stockmann et al., 2013; Umweltveränderungen, 2009). These numbers highlight the potential of conservation management practices adoption and SOC sequestration in subtropical climates.

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 conservation 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 feedbacks 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 conservation 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 tillage farming systems and its capacity to estimate the global impact of conservation agriculture.

5. Conclusions

Both crop yield and SOC stocks increased over time in Paiquerê farm and the ecosystem models provide similar simulations for SOC dynamics. However, the SOC stocks were higher and closer to the observed values in Century simulations compared to Roth-C. The corn yield showed the higher increase compared to soybean and wheat, about 3.0 Mg ha^{-1} in 16 years. The expansion of the results showed that conservation best management practices has the potential to sequester 2.7 ± 0.02 to 3.2 ± 0.02 Pg C in 60 years (0–20 cm depth) considering current and 15% increase in biomass C input. In the 30% and 15% decrease scenarios the sequestration were 2.2 ± 0.02 and 2.4 ± 0.02 Pg C at 0–20 cm an in 15% increase scenario it goes to 3.2 ± 0.02 Pg C. However, considering 0–100 cm depth, the SOC sequestration can be up to 4.8 ± 3 to 5.7 ± 3 Pg C in 60 years considering current and 15% increase in biomass-C input. This is equivalent to 6 years of global land use and land use change emissions, indicating that conservation best management practices are a promising tool to promote C sequestration in subtropical soils.

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References

Abebe, A., Pathak, H., Singh, S.D., Bhatia, A., Harit, R.C., Kumar, V., 2016. Growth, yield and quality of maize with elevated atmospheric carbon dioxide and temperature in north–west India. Agric. Ecosyst. Environ. 218, 66–72.
Ainsworth, E.A., Davey, P.A., Bernacchi, C.J., Dermody, O.C., Heaton, E.A., Moore, D.J., Morgan, P.B., Naidu, S.L., Yoo Ra, H.-s., Zhu, X.-g., Curtis, P.S., Long, S.P., 2002. A meta-analysis of elevated [CO2] effects on soybean (Glycine max) physiology, growth and yield. Glob. Chang. Biol. 8, 695–709.
Álvaro-Fuentes, J., Morell, F.J., Plaza-Bonilla, D., Arrúe, J.L., Cantero-Martínez, C., 2012. Modelling tillage and nitrogen fertilization effects on soil organic carbon dynamics. Soil Tillage Res. 120, 32–39.
Bhardwaj, A.K., Jasrotia, P., Hamilton, S.K., Robertson, G.P., 2011. Ecological management of intensively cropped agro-ecosystems improves soil quality with sustained productivity. Agric. Ecosyst. Environ. 140, 419–429.
Bontemps, S., Defourny, P., Bogaert, E.V., Arino, O., Kalogirou, V., Perez, J.R., 2011. GLOBCOVER 2009-Products Description and Validation Report.
Briedis, C., Sá, J.C.d.M., Caires, E.F., Navarro, J.d.F., Inagaki, T.M., Boer, A., Neto, C.Q., Ferreira, A.d.O., Canalli, L.B., Santos, J.B.d., 2012. Soil organic matter pools and carbon-protection mechanisms in aggregate classes influenced by surface liming in a no-till system. Geoderma 170, 80–88.
Castrolanda, 2014. Relatório anual, p. 76. Available in: https://www.castrolanda.coop.br/img/relatorio_anual/19RA2016/RA2016.pdf.
Carter, A.J., Scholes, R.J., 2000. Spatial global database of soil properties. IGBP global soil data task CD-ROM. In: International Geosphere-Biosphere Programme (IGBP) Data Information Systems. Toulouse, France.
Chen, X., Liu, J., Deng, Q., Yan, J., Zhang, D., 2012. Effects of elevated CO2 and nitrogen addition on soil organic carbon fractions in a subtropical forest. Plant Soil 357, 25–34.
Coleman, K., Jenkinson, D.S., 1996. RothC-26.3-A Model for the Turnover of Carbon in Soil. Evaluation of Soil Organic Matter Models. Springer, pp. 237–246.
Cotrufo, M.F., Soong, J.L., Horton, A.J., Campbell, E.E., Haddix, M.L., Wall, D.H., Parton, W.J., 2015. Formation of soil organic matter via biochemical and physical pathways of litter mass loss. Nat. Geosci. 8, 776–779.
De Oliveira Ferreira, A., Sá, J.C.d.M., Harms, M.G., Miara, S., Briedis, C., Quadros Netto, C., Santos, J.B.d., Canalli, L.B., 2012. Carbon balance and crop residue management in dynamic equilibrium under a no-till system in Campos Gerais. Rev. Bras. Ciência do Solo 36, 1583–1590.
De Oliveira Ferreira, A., Amado, T.J.C., Rice, C.W., Diaz, D.R., Briedis, C., Inagaki, T.M., Gonçalves, D.R.P., 2018. Driving factors of soil carbon accumulation in Oxisols in long-termno-till systems of South Brazil. Sci. Total Environ. 622–623, 735–742.
De Oliveira Ferreira, A., Amado, T., Rice, C.W., Diaz, D.aR., Keller, C., Inagaki, T.M., 2016. Can no-till grain production restore soil organic carbon to levels natural grass in a subtropical Oxisol? Agric. Ecosyst. Environ. 229, 13–20.
Del Grosso, S.J., Mosier, A.R., Parton, W.J., Ojima, D.S., 2005. DAYCENT model analysis of past and contemporary soil N 2 O and net greenhouse gas flux for major crops in the USA. Soil Tillage Res. 83, 9–24.
Dexter, A.R., 2004. Soil physical quality: part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. Geoderma 120, 201–214.

Diekow, J., Mielniczuk, J., Knicker, H., Bayer, C., Dick, D.P., Kögel-Knabner, I., 2005. Soil C and N stocks as affected by cropping systems and nitrogen fertilisation in a southern Brazil Acrisol managed under no-tillage for 17 years. Soil Tillage Res. 81, 87–95.

Djigal, D., Saj, S., Rabary, B., Blanchart, E., Villenave, C., 2012. Mulch type affects soil biological functioning and crop yield of conservation agriculture systems in a long-term experiment in Madagascar. Soil Tillage Res. 118, 11–21.

EMBRAPA, 2018. Vasques, g. D. M., dart, r. D. O., baca, j., ceddia, m., & mendonça santos, m. D. L. Mapa de estoque de carbono orgânico do solo (COS) a 0-30 cm do Brasil. Embrapa Solos-Outras publicações técnicas (INFOTECA-E).

ESRI, 2017. ArcGIS Desktop: Release 10. Environmental Systems Research Institute, Redlands, CA.

Fageria, N.K., 2000. Resposta de arroz de terras altas à correção de acidez em solo de cerrado. Pesqui. Agropecuária Bras. 35, 2303–2307.

Falloon, P., Smith, P., Coleman, K., Marshall, S., 2000. How important is inert organic matter for predictive soil carbon modelling using the Rothamsted carbon model? Soil Biol. Biochem. 32, 433–436.

Fang, C., 2005. Is resistant soil organic matter more sensitive to temperature then the labile organic matter? Biogeosci. Discuss. 2, 725–735.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O/'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockstrom, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478, 337–342.

Frísia, 2015. Relatório anual, p. 64. Available in: http://www.frisia.coop.br/pt-BR/cooperativa/Paginas/relatorio-anual.aspx.

Gee, G.W., Bauder, J.W., Klute, A., 1986. Particle-size analysis. Methods of soil analysis. Part 1. Phys. Mineral. Meth. 383–411.

Gonçalves, D.R.P., Sá, J.C.d.M., Fornari, A.J., Furlan, F.J.F., Ferreira, L.A., de Oliveira Ferreira, A., 2015. Total carbon and labile fractions inventory and mapping by soil orders under long-term No-till farming to promote precision agriculture. Soil-Spec. Farm.: Precis. Agric. 22, 307.

Gonçalves, D.R.P., Sá, J.C.d.M., Mishra, U., Cerri, C.E.P., Ferreira, L.A., Furlan, F.J.F., 2017. Soil type and texture impacts on soil organic carbon storage in a sub-tropical agro-ecosystem. Geoderma 286, 88–97.

Grossman, R.B., Reinsch, T.G., 2002. 2.1 Bulk density and linear extensibility. Meth. Soil Anal.: Part 4 Phys. Meth. 201–228.

Han, X., Hao, X., Lam, S.K., Wang, H., Li, Y., Wheeler, T., Ju, H., Lin, E., 2015. Yield and nitrogen accumulation and partitioning in winter wheat under elevated CO2: a 3-year free-air CO2 enrichment experiment. Agric. Ecosyst. Environ. 209, 132–137.

Hao, X., Gao, J., Han, X., Ma, Z., Merchant, A., Ju, H., Li, P., Yang, W., Gao, Z., Lin, E., 2014. Effects of open-air elevated atmospheric CO2 concentration on yield quality of soybean (Glycine max (L.) Merr). Agric. Ecosyst. Environ. 192, 80–84.

Hok, L., Sá, J.C.d.M., Reyes, M., Boulakia, S., Tivet, F., Leng, V., Kong, R., Briedis, C., Hartman, D.C., Ferreira, L.A., Inagaki, T.M., Gonçalves, D.R.P., Bressan, P.T., 2018. Enzymes and C pools as indicators of C build up in short-term conservation agriculture in a savanna ecosystem in Cambodia. Soil Tillage Res. 177, 125–133.

Inagaki, T.M., Sá, J.C.d.M., Caires, E.F., Gonçalves, D.R.P., 2017. Why does carbon increase in highly weathered soil under no-till upon lime and gypsum use? Sci. Total Environ. 599, 523–532.

Kirkby, C.A., Richardson, A.E., Wade, L.J., Batten, G.D., Blanchard, C., Kirkegaard, J.A., 2013. Carbon-nutrient stoichiometry to increase soil carbon sequestration. Soil Biol. Biochem. 60, 77–86.

Kirkby, C.A., Richardson, A.E., Wade, L.J., Passioura, J.B., Batten, G.D., Blanchard, C., Kirkegaard, J.A., 2014. Nutrient availability limits carbon sequestration in arable soils. Soil Biol. Biochem. 68, 402–409.

Kuhn, N.J., Hu, Y., Bloemertz, L., He, J., Li, H., Greenwood, P., 2016. Conservation tillage and sustainable intensification of agriculture: regional vs. global benefit analysis. Agric. Ecosyst. Environ. 216, 155–165.

Ladha, J.K., Rao, A.N., Raman, A.K., Padre, A.T., Dobermann, A., Gathala, M., Kumar, V., Saharawat, Y., Sharma, S., Piepho, H.P., 2016. Agronomic improvements can make future cereal systems in South Asia far more productive and result in a lower environmental footprint. Glob. Chang. Biol. 22, 1054–1074.

Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304, 1623–1627.

Leite, L.F.C., Mendonça, E.S., 2003. Modelo century de dinâmica da matéria orgânica do solo: Equações e pressupostos. Ciência Rural. 33, 679–686.

Li, D., Liu, H., Qiao, Y., Wang, Y., Cai, Z., Dong, B., Shi, C., Liu, Y., Li, X., Liu, M., 2013. Effects of elevated CO2 on the growth, seed yield, and water use efficiency of soybean (Glycine max (L.) Merr.) under drought stress. Agric. Water Manag. 129, 105–112.

Maack, R., 1981. Geografia física do Estado do Paraná. J. Olympio.

Meng, F., Zhang, J., Yao, F., Hao, C., 2014. Interactive effects of elevated CO2 concentration and irrigation on photosynthetic parameters and yield of maize in Northeast China. PLoS One 9, 1–13.

Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.-S., Cheng, K., Das, B.S., Field, D.J., Gimona, A., Hedley, C.B., Hong, S.Y., Mandal, B., Marchant, B.P., Martin, M., McConkey, B.G., Mulder, V.L., O'Rourke, S., Richer-de-Forges, A.C., Odeh, I., Padarian, J., Paustian, K., Pan, G., Poggio, L., Savin, I., Stolbovoy, V., Stockmann, U., Sulaeman, Y., Tsui, C.-C., Vågen, T.-G., van Wesemael, B., Winowiecki, L., 2017. Soil carbon 4 per mille. Geoderma 292, 59–86.

Mishra, U., Lal, R., Liu, D., Van Meirvenne, M., 2010. Predicting the spatial variation of the soil organic carbon pool at a regional scale. Soil Sci. Soc. Am. J. 74, 906.

Nachtergaele, F., Van Velthuizen, H., Verelst, L., 2008. Harmonized World Soil Database, Version 1.0. FAO, Rome.

Nadeu, E., Gobin, A., Fiener, P., Wesemael, B., Oost, K., 2015. Modelling the impact of agricultural management on soil carbon stocks at the regional scale: the role of lateral fluxes. Glob. Chang. Biol. 21, 3181–3192.

O'Leary, G.J., Christy, B., Nuttall, J., Huth, N., Cammarano, D., Stöckle, C., Basso, B., Shcherbak, I., Fitzgerald, G., Luo, Q., Farre-Codina, I., Palta, J., Asseng, S., 2015. Response of wheat growth, grain yield and water use to elevated CO2 under a Free-Air CO2 Enrichment (FACE) experiment and modelling in a semi-arid environment. Glob. Chang. Biol. 21, 2670–2686.

Ogle, S.M., Breidt, F.J., Easter, M., Williams, S., Killian, K., Paustian, K., 2010. Scale and uncertainty in modeled soil organic carbon stock changes for US croplands using a process-based model. Glob. Chang. Biol. 16, 810–822.

Ogle, S.M., Breidt, F.J., Easter, M., Williams, S., Paustian, K., 2007. An empirically based approach for estimating uncertainty associated with modelling carbon sequestration in soils. Ecol. Model. 205, 453–463.

Ogle, S.M., Swan, A., Paustian, K., 2012. No-till management impacts on crop productivity, carbon input and soil carbon sequestration. Agric. Ecosyst. Environ. 149, 37–49.

Pachauri, R.K., Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R., Church, J.A., Clarke, L., Dahe, Q., Dasgupta, P., 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC.

Parton, W.J., Stewart, J.W.B., Cole, C.V., 1988. Dynamics of C, N, P and S in grassland soils: a model. Biogeochemistry 5, 109–131.

Pillar, V.D.P., Müller, S.C., Castilhos, Z.M.d.S., Jacques, A.V.Á., 2009. Campos Sulinos-conservação e uso sustentável da biodiversidade. Ministério do Meio Ambiente-MMA.

Pittelkow, C.M., Liang, X., Linquist, B.A., Van Groenigen, K.J., Lee, J., Lundy, M.E., van Gestel, N., Six, J., Venterea, R.T., van Kessel, C., 2015. Productivity limits and potentials of the principles of conservation agriculture. Nature 517, 365–368.

Post, W.M., Izaurralde, R.C., West, T.O., Liebig, M.A., King, A.W., 2012. Management opportunities for enhancing terrestrial carbon dioxide sinks. Front. Ecol. Environ. 10, 554–561.

Powlson, D.S., Stirling, C.M., Jat, M.L., Gerard, B.G., Palm, C.A., Sanchez, P.A., Cassman, K.G., 2014. Limited potential of no-till agriculture for climate change mitigation. Nat. Clim. Change 4, 678–683.

R Development Core Team, 2017. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Rasmussen, P.L., Goulding, K.W.T., Briwn, J.R., Grace, P.R., Janzen, H.H., Körschens, M., 1998. Long-term agroecosystem experiments: assessing agricultural sustainability and global change. Science 282.

Reichstein, M., 2005. Does the temperature sensitivity of decomposition vary with soil organic matter quality? Biogeosci. Discuss. 2, 737–747.

Rubel, F., Kottek, M., 2010. Observed and projected climate shifts 1901–2100 depicted by world maps of the Köppen-Geiger climate classification. Meteorol. Z. 19, 135–141.

Rustad, L.E., 2001. A meta-analysis of the response of soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming. Oecologia 126, 543–562.

Sá, J.C.d.M., Cerri, C.C., Dick, W.A., Lal, R., Venske Filho, S.P., Piccolo, M.C., Feigl, B.E., 2001. Organic matter dynamics and carbon sequestration rates for a tillage chronosequence in a Brazilian oxisol. Soil Sci. Soc. Am. J. 65, 1486–1499.

Sá, J.C.d.M., Séguy, L., Tivet, F., Lal, R., Bouzinac, S., Borszowskei, P.R., et al., 2015. Carbon depletion by plowing and its restoration by no-till cropping systems in Oxisols of subtropical and tropical Agro-ecoregions in Brazil. Land Degrad. Dev. 26, 531–543.

Sá, J.C.M., Lal, R., Cerri, C.C., Lorenz, K., Hungria, M., de Faccio Carvalho, P.C., 2017. Low-carbon agriculture in South America to mitigate global climate change and advance food security. Environ. Int. 98, 102–112.

Sá, J.C.d.M., Tivet, F., Lal, R., Briedis, C., Hartman, D.C., dos Santos, J.Z., dos Santos, J.B., 2014. Long-term tillage systems impacts on soil C dynamics, soil resilience and agronomic productivity of a Brazilian Oxisol. Soil Tillage Res. 136, 38–50.

Saidy, A.R., Smernik, R.J., Baldock, J.A., Kaiser, K., Sanderman, J., Macdonald, L.M., 2012. Effects of clay mineralogy and hydrous iron oxides on labile organic carbon stabilisation. Geoderma 173–174, 104–110.

Soil Survey, S., 2014. Keys to Soil Taxonomy. Soil Conservation Service, Washington DC.

Solos, E., 1999. Sistema brasileiro de classificação de solos. Rio de Janeiro, p. 412.

Stockmann, U., Adams, M.A., Crawford, J.W., Field, D.J., Henakaarchchi, N., Jenkins, M., Minasny, B., McBratney, A.B., de Courcelles, V.d.R., Singh, K., 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agric. Ecosyst. Environ. 164, 80–99.

Tivet, F., Sá, J.C.d.M., Lal, R., Briedis, C., Borszowskei, P.R., dos Santos, J.B., Farias, A., Eurich, G., da Cruz Hartman, D., Junior, M.N., 2013. Aggregate C depletion by plowing and its restoration by diverse biomass-C inputs under no-till in subtropical and tropical regions of Brazil. Soil Tillage Res. 126, 203–218.

Umweltveränderungen, W.B.G., 2009. Die Anrechnung biologischer Quellen und Senken im Kyoto-Protokoll: Fortschritt oder Rückschlag für den globalen Umweltschutz? Sondergutachten, 1998.

VandenBygaart, A.J., 2016. The myth that no-till can mitigate global climate change. Agric. Ecosyst. Environ. 216, 98–99.
Villarino, S.H., Studdert, G.A., Laterra, P., Cendoya, M.G., 2014. Agricultural impact on soil organic carbon content: testing the IPCC carbon accounting method for evaluations at county scale. Agric. Ecosyst. Environ. 185, 118–132.
Wang, L., Feng, Z., Schjoerring, J.K., 2013. Effects of elevated atmospheric CO2 on physiology and yield of wheat (Triticum aestivum L.): a meta-analytic test of current hypotheses. Agric. Ecosyst. Environ. 178, 57–63.
Zanatta, J.A., Bayer, C., Dieckow, J., Vieira, F.C.B., Mielniczuk, J., 2007. Soil organic carbon accumulation and carbon costs related to tillage, cropping systems and nitrogen fertilization in a subtropical Acrisol. Soil Tillage Res. 94, 510–519.