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Assessing strategies to enhance soil carbon sequestration with the DSSAT-CENTURY model

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Abstract

The adoption of no-till (NT) has been proposed to recover soil organic carbon (SOC), which will aid the mitigation of climate change. However, studies have questioned the potential of NT soils to deliver SOC sequestration and sustain crop yields. No-till experiments are relatively recent (<50 years) and very few studies were able to assess SOC dynamics in high-yield agroecosystems. We used the DSSAT-CENTURY model to predict long-term SOC (0–30 cm) using datasets from two experiments assessing tillage and nitrogen (N) sources in a Mollisol from the midwest United States (28 years) and tillage and crop rotations in an Oxisol from southern Brazil (33 years). The conversion of prairie and grassland soils to conventional agriculture decreased SOC by 61 and 12% in the Mollisol and Oxisol, respectively. Soil organic C accrual in NT soils was >0.5 Mg C ha^{-1} $year^{-1}$ under medium-low-yield maize in the Mollisol and negligible in the Oxisol under soybean/wheat rotation. Organic fertilization and crop rotation increased SOC accrual at both sites. Simulated SOC had good agreement with observations for NT soils but overestimated SOC in tilled soils. The model's parameters were then modified for tilled soils. Long-term simulations (100 years) revealed that SOC accrual in NT soils (0–15 cm) is partially offset by losses at 15–30 cm under low C inputs. Simulations with best crop management practices (BP; irrigation, high-yield cultivars, higher plant density and improved N fertilization) augmented C inputs and SOC stocks, ultimately recovering SOC to the levels of prairie soils. Our results suggest that the adoption of NT, recycling of organic fertilizers and the use of BP should be further promoted for recovery and permanence of SOC in agricultural soils.

Highlights

- Studies have questioned the potential of conservation agriculture (CA) to deliver SOC sequestration and sustain crop yields.
- We used the DSSAT-CENTURY model to simulate SOC dynamics in temperate and subtropical soils.
- No-till under moderate C/N inputs recovered topsoil SOC, but subsurface losses offset SOC accrual.

- Use of CA, organic amendments and best practice crop management (BP) is crucial for long-term SOC storage and permanence.

KEYWORDS

best crop management practices, conservation agriculture, modelling, soil organic matter

1 | INTRODUCTION

Conversion of native ecosystems to intensively tilled agriculture has depleted soil organic carbon (SOC) and contributed 133 Pg C to the atmospheric CO_2 concentrations over the past 12,000 years (Sanderman, Hengl, & Fiske, 2017). Depletion of SOC leads to a decline in soil quality and a reduction in ecosystems services, ultimately threatening food security (Lal, 2010). Conservation agriculture (CA), as defined by minimal soil disturbance, permanent soil cover and crop rotation, has been proposed to recover SOC and soil quality, thus providing food security and promoting climate change adaptation and mitigation (Jat, Sahrawat, Kassam, & Friedrich, 2014; Lal, 2016; Minasny et al., 2017). No-till (NT) is considered a key component of CA because it addresses two of its principles, which are planting through soil cover with minimum disturbance.

The adoption of NT recovers SOC, although only partially offsetting initial losses from the soils of native ecosystems (Luo, Wang, & Sun, 2010; Kopittke, Dalal, Finn, & Menzies, 2017). However, NT experiments are relatively recent (<50 years) and generally assess agroecosystems with low- to moderate-inputs in order to replicate regional agricultural practices (Bayer, Martin-Neto, Mielniczuk, Pavinato, & Dieckow, 2006; Boddey et al., 2010; Corbeels et al., 2016; Follett, Jantalia, & Halvorson, 2013; Martínez et al., 2016; Olson, Ebelhar, & Lang, 2013; Poffenbarger et al., 2017; Poirier et al., 2009; Stewart, Halvorson, & Delgado, 2017). Very few studies were able to assess long-term SOC dynamics in high-yield agroecosystems (Cook & Trlica, 2016; Grassini & Cassman, 2012; Grassini, Specht, Tollenaar, Ciampitti, & Cassman, 2015; Walia, Baer, Krausz, & Cook, 2017). Consequently, recent studies have questioned the potential of NT soils to sustain crop yields (Pittelkow et al., 2014, 2015), promote SOC accrual in comparison with tilled soils and mitigate climate change (Corbeels et al., 2016; Powlson et al., 2014).

The importance of crop productivity and C inputs for SOC accrual in NT soils has been extensively demonstrated (Ogle, Swan, & Paustian, 2012; Powlson et al., 2012). Crop productivity and SOC accrual in NT soils are favoured by increased nutrient availability (de Oliveira Ferreira et al., 2018; Kirkby et al., 2014; Manzoni, Taylor, Richter, Porporato, & Ågren, 2012; Poffenbarger et al., 2017; Van Groenigen et al., 2017), amelioration of subsoil acidity (Dalla Nora, Amado, & Nicoloso, R. da S., & Gruhn, E.M., 2017; de Oliveira Ferreira, Amado, et al., 2018), use of organic amendments (Poulton, Johnston, MacDonald, White, & Powlson, 2018; Powlson et al., 2012; Xia, Lam, Yan, & Chen, 2017), irrigation and other best crop management practices (BP), such as high-yield cultivars with increased plant density (Follett et al., 2013; Grassini & Cassman, 2012; Grassini, Thorburn, Burr, & Cassman, 2011; Schwalbert et al., 2018; Stewart et al., 2017). Thus, the adoption of BP could increase SOC accrual in NT soils up to the levels of natural soils (de Oliveira Ferreira et al., 2016, 2018).

We tested this hypothesis using the CENTURY module included in the Decision Support System for Agrotechnology Transfer (DSSAT) software (Hoogenboom et al., 2015; Porter et al., 2010) to simulate long-term SOC dynamics in two long-term experiments from the midwest United States and southern Brazil. The DSSAT-CENTURY model has been used to simulate SOC dynamics in both low- and high-yield agroecosystems (Gijsman, Hoogenboom, Parton, & Kerridge, 2002; Li, Yang, Drury, & Hoogenboom, 2015; Liu et al., 2017; Musinguzi et al., 2014). The experiments included in our study tested different soil tillage systems, nitrogen (N) sources and crop rotation with frequent plant and soil sampling. These unique datasets allowed us to predict long-term SOC dynamics with the DSSAT-CENTURY model and test the potential of NT soils for SOC sequestration in temperate and subtropical agroecosystems.

2 | MATERIAL AND METHODS

2.1 | Long-term experiments

We used datasets (Nicoloso, 2009; Boddey et al., 2010; De Campos, Amado, Bayer, da Nicoloso, & Fiorin, 2011; de Oliveira Ferreira et al., 2013; Nicoloso, Rice, Amado, Costa, & Akley, 2018) collected from two long-term experiments located at the Technology Unit of the Central Cooperative Gaucha Ltd. (CCGL-TEC) in Cruz Alta, RS, Brazil (28°36′01.0″S, 53°40′20.6″W, elev. 432 m, slope

3%) and at the North Farm of the Department of Agronomy, Kansas State University in Manhattan, KS, USA (39°12′41.7″N, 96°35′38.7″W, elev. 323 m, slope 0%).

2.1.1 | Cruz Alta, RS, Brazil

The soil in Cruz Alta was a Typic Haplorthox or Oxisol (U.S. Soil Taxonomy) or Rhodic Ferrasol (IUSS Working Group WRB, 2015) and the climate was classified as humid subtropical (Cfa), with mean annual precipitation of 1,750 mm and temperature of 19.2°C. The area had been under cultivation since 1965 with wheat (*Triticum aestivum*) and soybean (*Glycine max*) double cropping (winter/summer) under disk tillage (1965–1980) and reduced tillage (1980–1985) (de Oliveira Ferreira et al., 2016). Lime (5 Mg ha^{-1}) was incorporated before the experiment was established in 1985 to test two soil tillage systems in the main plots and three cropping systems in subplots. The field experiment had no replicated plots. The soil tillage systems were disk tillage (DT) and no-till (NT). The DT treatment had slight variations over the years. Until 2001, tillage operations consisted of one pass of a chisel plough (15 cm) and two passes of a disk harrow (8 cm) before planting winter crops and one pass of a disk plough and two passes of a disk harrow before planting summer crops (Campos, Reinert, Nicolodi, Ruedell, & Petrere, 1995; Jantalia et al., 2006). Later, both winter and summer crops were planted after one pass of a disk plough (12 cm) and two passes of a disk harrow (De Campos et al., 2011; de Oliveira Ferreira et al., 2013). All crops in the NT treatment were planted through the crop residues with minimal soil disturbance. The tested cropping systems were (winter/summer): wheat/soybean (R0), wheat/soybean/black oats (*Avena strigosa*)/soybean (R1), and wheat/soybean/black oats/soybean/black oats + vetch (*Vicia sativa*)/maize (*Zea mays*)/radish (*Raphanus sativus*) (R2). Radish was first introduced in rotation R2 in 1996. Small grain crops (wheat, oats, vetch and radish) were seeded using a double disk drill (5 cm) with 22-cm spaced rows. Soybean and maize were planted in rows spaced 45 cm apart using a planter equipped with coulter blades, shanks for fertilizer banding (18 cm) and a double disk for sowing seeds (8 cm). Wheat and maize received 60 and 90 kg N ha^{-1} in each cropping season, whereas other crops received no N fertilization. The P and K fertilization followed soil-test nutrient recommendations until 2000, when a standard annual fertilization rate of 50 kg ha^{-1} of P_2O_5 and K_2O was adopted for all cropping systems (Boddey et al., 2010; De Campos et al., 2011). Lime was applied again in 1995 (5 Mg ha^{-1}) without incorporation in the NT plots.

2.1.2 | Manhattan, KS, USA

The Manhattan experiment was established in 1990 in plots with corn under contrasting soil tillage systems and subplots with N sources. Replicated plots were arranged in four randomized blocks. The soil was a moderately well-drained Kennebec silt loam (a fine-silty, mixed, superactive, mesic Cumulic Hapludoll; Soil Survey Staff, 2014) or Haplic Chernozem (IUSS Working Group WRB, 2015). The climate was classified as humid continental (Dfa), with a mean annual precipitation of 800 mm and temperature of 11.4°C. The area had been cultivated with wheat and other small grains under intensive tillage since the 1930s. Two tillage systems were tested in the main plots: chisel tillage (CT) and NT. For CT, tillage consisted of one pass of a straight point chisel plough (15 cm) in the autumn and two passes of a disk harrow (8 cm) in the spring. Maize was planted with a planter equipped with coulter blades and double disks for seeds (8 cm). The N sources applied in the subplots were 168 kg available-N ha^{-1}, either with mineral (MF) or organic fertilizers (OF), besides a control treatment (CO) without N. The mineral fertilizers used were either ammonium nitrate (1990–1996) or urea. From 1990 to 2001, the organic fertilizer was a solid cattle manure collected from the Kansas State University Beef Stocker Unit. Since 2002, the OF has been composted organic waste from the North Farm composting facility at Kansas State University. The OF was analysed for total and ammonium-N contents and the application rates were calculated considering that 30% of organic N content was available during each cropping season (Mikha & Rice, 2004). Both mineral and organic fertilizers were broadcast on the soil surface before maize planting. For CT plots, the fertilizers were incorporated with one pass of a disk harrow (8 cm).

2.2 | Soil and crop data

Stover biomass production was obtained from both experimental sites. We recovered data from 21 out of 28 years from the Manhattan experiment and for the crops cultivated during the 1985–2004 period from the Cruz Alta experiment (Campos, 2006). Soil organic carbon content and bulk density in the 0–5, 5–15 and 15–30-cm depths were determined in 1990, 1992, 1995, 1997, 1999, 2002, 2003, 2004, 2007 and 2014 in Manhattan (Nicoloso et al., 2018). Sample depths varied in the Cruz Alta experiment. Soil was sampled from the 0–20-cm depth at the beginning of the experiment in 1985 (De Campos et al., 2011). Samples were collected from the 0–5, 5–10, 10–15, 15–20 and 20–30-cm depths in 2002 (Boddey et al., 2010), from the 0–5, 5–10, 10–20 and 20–30-cm depths in 2004 (De Campos et al., 2011), and from the 0–5, 5–15 and 15–30-cm depths in 2007 and 2010 (de Oliveira Ferreira et al., 2013; Nicoloso, 2009). About two to three subsamples were taken for one composite soil sample from each sub-plot (Boddey et al., 2010; De Campos et al., 2011; de Oliveira Ferreira et al., 2013; Nicoloso, 2009; Nicoloso et al., 2018). Prairie and grassland soils from the surroundings of the respective experimental sites (<2,000 m) were sampled in the 0–5, 5–15 and 15–30-cm depths to estimate original SOC in both locations (de Oliveira Ferreira et al., 2016; Nicoloso, 2009). A factor of 1.14 was used to correct SOC content in samples from 1985 and 2004 that were analysed by wet combustion in the Cruz Alta experiment (Dos Santos Rheinheimer, De Campos, Giacomini, Conceição, & Bortoluzzi, 2008). All other samples from Cruz Alta and Manhattan were analysed by dry combustion with a CN elemental analyser (Flash EA 1112 Series, ThermoScientific, Waltham, MA, USA). Soil organic carbon stocks were calculated for each sampling depth, treatment and year using soil bulk density and SOC content. Soil organic carbon stocks were then recalculated on the basis of equivalent soil masses (Wendt & Hauser, 2013), using as references the soil bulk density measured in the 0–5, 5–15 and 15–30-cm depths in 1990 in Manhattan and in the grassland soil in Cruz Alta (Table S1).

2.3 | Calibration and validation of the DSSAT-CENTURY model

We used the CENTURY module included in DSSAT 4.6.1.0 (Hoogenboom et al., 2015) to simulate SOC dynamics in the two long-term experiments included in this study. The required input data included soil profile and initial conditions (Table S1), detailed soil and crop management (Tables S2–S5) and daily weather. The weather data, including daily rainfall (mm) and maximum and minimum temperature (°C), were obtained from the CCGL-TEC weather station, ~350 m from the Cruz Alta experimental site (available at http://www.inmet.gov.br/projetos/rede/pesquisa/), and from the Manhattan weather station (USC00144972), ~2,000 m from the Manhattan experimental site (available at https://www.ncdc.noaa.gov/ghcn-daily-description). We used the DSSAT-Weatherman program (Pickering et al., 1994) to estimate daily solar radiation (MJ m^{-2}), corrected for erroneous or missing data, and to generate a climate data summary for both experimental sites (-Figure S1). Crop cultivars varied during the experimental period at both sites, but no detailed records were kept. Thus, we used generic crop cultivars (Table S3) to simulate average biomass production in each treatment (Table 3). Nonetheless, DSSAT 4.6.0.1 did not have crop models for simulation of black oat, radish or plant mixtures such as black oat + vetch. Thus, we created generic plants for simulation of black oat and radish crops based on DSSAT existing barley and canola genotypes. The vetch crop was not simulated, but applied as a crop residue concomitantly with black oat harvest (Table S5).

We conducted spin-up simulations to estimate initial stable SOC pools for both sites (Basso et al., 2011) using the SOC measured in the prairie and grassland soils as initial total SOC stocks, the baseline SOC stocks as measured in 1985 in Cruz Alta and 1990 in Manhattan, and the soil and crop management practices used in the areas before the establishment of the experiments. We then ran trial tests to simulate SOC using crop, fertilizer and tillage practices used in CT MF and NT MF treatments in Manhattan and DT R1 and NT R1 treatments from the Cruz Alta site. These treatments were selected for the calibration of the model because they were representative of the regional agricultural practices used in both locations. Both spin-up simulations and trial runs were performed using DSSAT-CENTURY default parametrization. The results showed good agreement with observations for NT soils at both locations. However, modelled SOC was overestimated for CT and DT treatments in both experiments. Both procedures (spin-up simulations and trial runs) were repeated for CT MF and NT MF treatments in Manhattan and DT R1 and NT R1 treatments from the Cruz Alta site, with modifications of the SOC decomposition parameters (Porter et al., 2010) until SOC predicted by the DSSAT-CENTURY model had good agreement with observations in all treatments selected for calibration. The model required modifications of default respiration losses from both metabolic and structural litter decomposition for tilled soils in both locations (Table 1) following a previous study with the Century 4.5 model (Weber, Mielniczuk, & Tornquist, 2016). No modifications of any of the default parameters of the DSSAT-CENTURY model were required for NT soils.

The model calibrated with default and modified parameters for NT and tilled soils, respectively, was then validated using the other treatments available in both experiments: CT CO, CT OF, NT CO and NT OF in Manhattan, and DT R0, DT R2, NT R0 and NT R2 in Cruz Alta. Although using treatments from the same experimental sites, the model was validated with an independent dataset with a greater number of observations from treatments that were not used for the calibration procedure (Musinguzi et al., 2014; Weber et al., 2016). The use of treatments with N inputs and crop rotations for the validation phase helped to test the accuracy of the model

TABLE 1 Decomposition rate parameters of the DSSAT-CENTURY model used in this study[a]

		Respiration losses[b]		
C pool (from)	**C pool (to)**	**NT (default)**	**CT (Manhattan)**	**DT (Cruz Alta)**
Metabolic litter	SOM1 (surface)	0.55	0.75	0.6
	SOM1 (soil)	0.55	0.75	0.6
Structural litter	SOM1 (surface)	0.45	0.75	0.6
	SOM1 (soil)	0.55	0.75	0.6
Structural litter	SOM2 (surface)	0.3	0.75	0.6
	SOM2 (soil)	0.3	0.75	0.6

[a] Adapted from Porter et al. (2010). Metabolic litter: easily decomposable fresh residue; structural litter: recalcitrant fresh residue; SOM1: microbial or active soil organic matter; SOM2: recalcitrant and partially stabilized soil organic matter.

[b] Fraction of carbon lost as CO_2 during decomposition process.

in simulating SOC under contrasting tillage practices and biomass inputs (Bruun, Christensen, Hansen, Magid, & Jensen, 2003). Following previous work, results were evaluated using the lack-of-fit (LOFIT), root mean square error (RMSE), modelling efficiency (EF), coefficient of determination (CD), relative error (E), mean difference (M) and correlation coefficient (r) tests (Smith, Powlson, McGill, & Arah, 1997).

2.4 | Long-term simulations of soil organic carbon

With the validation of the parameters of the model, we ran long-term simulations (100 years) of SOC according to the treatments tested in both experiments. These simulations were performed using the stochastic weather generators WGEN (Manhattan) and SIMMETEO (Cruz Alta) included in DSSAT. Weather generators were selected based on the completeness of the weather series (Soltani & Hoogenboom, 2003) and the correlations of modelled SOC with observations at both sites (Table 1). All simulations using weather generators were replicated 20 times. Alternative scenarios were also tested, including the adoption of BP for both sites with the use of high-yield crop cultivars and higher maize plant density (Table S3), increased and split N fertilization (Table S4) and irrigation (sprinkle applications set as automatic when necessary).

3 | RESULTS AND DISCUSSION

3.1 | Calibration and validation of the DSSAT-CENTURY model

The spin-up simulations and trial runs using DSSAT-CENTURY default parameters for litter and SOC decomposition overestimated SOC in CT and DT treatments in both experiments (data not shown). Previous studies suggested site-specific calibrations with modifications of the "cultivation factor" used in the CENTURY model as a unitless multiplier to increase SOC and structural litter decomposition rates for a period of 30 days after tillage or incorporation of organic residues into the soil (Bolinder, VandenBygaart, Gregorich, Angers, & Janzen, 2006; Porter et al., 2010; Weber et al., 2016). Simulations using this approach required increasing the default cultivation factor from 1.6 up to 20.0 (+1,150%) to decrease the overestimation of SOC stocks in the CT treatment from Manhattan. Using these parameters, the SOC mineralization modelled to occur within the period (92 days each year) when the cultivation factor was affecting SOC decomposition rates in the Mollisol site increased from 24.2 to 54.6% of the total SOC mineralization predicted by the model (data not shown). These results were considered unrealistic in comparison with previous studies that reported no differences in SOC mineralization from tilled and NT soils with residues removed (Pes, Amado, La Scala, Bayer, & Fiorin, 2011) or soil aggregates disrupted (Awale, Emeson, & Machado, 2017; Razafimbelo et al., 2008).

Another assumption of the CENTURY model is that 55% of metabolic and 45% of structural litter C assimilated by microbial biomass on the soil surface is lost as CO_2 (Parton, Schimel, Cole, & Ojima, 1987; Porter et al., 2010). Moreover, respiration losses are assumed to be 55% for both metabolic and structural litter C when assimilated by microbial biomass in the soil and 30% for structural litter C when transferred to the slow SOC pool (Parton et al., 1987; Porter et al., 2010). These values were established for grassland soils considering fungi as the primary decomposers of surface litter with higher carbon use efficiency (CUE) and representing a higher proportion of soil microbial biomass than bacteria (Parton et al., 1987; Six, Frey, Thiet, & Batten, 2006).

Respiration losses are also assumed to be constant regardless of soil tillage and are not affected by the cultivation factor, despite evidence showing great variability in CUE (10–78%) in soils with mixed microbial populations (for review see Manzoni et al., 2012; Six et al., 2006). A previous study reported higher fungal biomass and recovery of ^{13}C- and ^{15}N-labelled grain sorghum residues as SOC in NT than CT soils, although residue C mineralization was similar in both tillage systems (White & Rice, 2009). Higher microbial biomass increased SOC stabilization in NT soils due to occlusion of fresh plant C within large soil aggregates in both Oxisols and Mollisols (Fabrizzi et al., 2009; Six, Bossuyt, Degryze, & Denef, 2004; White & Rice, 2009).

Assuming that respiration losses from both metabolic and structural litter were likely to be higher in tilled than NT soils (Ogle et al., 2012), we increased the default values of the CENTURY module by 36–150% for CT soils (up to 75%) at the Manhattan site and by 9–100% for DT soils (up to 60%) at the Cruz Alta site (Table 1). Lower respiration losses were expected in heavy clayey Oxisols with high Fe-oxides content (51–56% of clay with 63.5 mg Fe-oxides g^{-1} soil as measured in Cruz Alta; Pes et al. (2011)) due to higher SOC stabilization promoted by organo-mineral interactions (Razafimbelo et al., 2008). Nonetheless, default values were maintained for NT soils at both sites considering that soil disturbances were minimal and respiration losses during litter decomposition were likely to be similar to grassland ecosystems such as those used for the original calibration of the CENTURY model (Parton et al., 1987). This approach yielded excellent agreement of modelled SOC and crop biomass production with observations at both sites with either measured and simulated weather data (Figure 1, Tables 2 and 3).

TABLE 2 Statistical analysis of soil organic carbon as predicted by the DSSAT model

Statistics	Weather data	
	Measured	Simulated (20 replications)
n	73	73
LOFIT (*P*-value)[a]	0.808	0.918
RMSE[b]	5.361	5.129
RMSE 95% CI	11.020	11.020
Modelling efficiency (EF)[c]	0.882	0.892
Coefficient of determination (CD)[d]	1.203	1.360
Relative error (E)[e]	−0.216	−0.139
E 95% CI	7.756	7.756
Mean difference (M) t-value[6]	0.067	0.167
P-value for M	.859	.642
r	0.940	0.949
P-value for *r*	<.001	<.001

[a] LOFIT (lack-of-fit test): $P < 0.05$ indicates that the total error in the simulated values was significantly greater than the error inherent in the measured values.

[b] RMSE (root mean square error): RMSE < RMSE 95% CI indicates that the simulated values fall within the 95% confidence interval of the measurements.

[c] EF can be negative or positive with a maximum value of 1 and positive values indicating that simulated values describe the trend in the measured data better than the mean of observations.

[d] CD ≥ 1 indicates that the deviation of the simulated values from the mean of measured values was less than observed in the measurements.

[e] E < E 95% CI indicates that the bias in the simulation was less than the 95% confidence interval of the measurements. 6t-value for the mean difference between simulated and measures values. A t-value greater than the critical two-tailed 2.5% t-value indicates that the simulation showed a significant bias when compared to measured values.

3.2 | Long-term simulations using the DSSAT-CENTURY model

Soil organic carbon stocks decreased by 61 and 12% due to the conversion of the prairie and grassland to agriculture under intensive soil tillage until 1990 in Manhattan and 1985 in Cruz Alta, respectively (Figure 1). These values are within the range (−0.2 to 65%) observed for SOC losses in the 0–30-cm soil layer due to the conversion of grassland to agriculture in a global assessment (Sanderman et al., 2017). Although higher SOC losses would be expected in warmer agroecosystems in response to the cultivation of grassland soils (Ogle, Breidt, & Paustian, 2005), losses were lower in Cruz Alta due to the shorter cultivation period (20 years), higher clay and Fe-oxides contents in the Oxisol (Razafimbelo et al., 2008), and the higher contents of stable SOC in the grassland soil (Table S1). The fraction of stable SOC estimated for the prairie soil in Manhattan (36%) was similar to the default values (34%) calibrated for temperate grassland soils in the CENTURY module (Gijsman et al., 2002; Parton et al., 1987). Nonetheless, the fraction of stable SOC estimated for the Manhattan site (61% of total SOC on average for tillage and fertilizer treatments in 1996) was close to the results from a previous assessment carried out in 1995 and 1996, when stable SOC averaged 58% of total SOC (Espinoza, 1997). For the Cruz Alta site, our estimate of the proportion of stable SOC in the grassland soil (74%) was comparable to values measured in a Brazilian Acrisol (70%) with similar clay content (46%) under natural vegetation (Carvalho Leite, De Sá Mendonça,

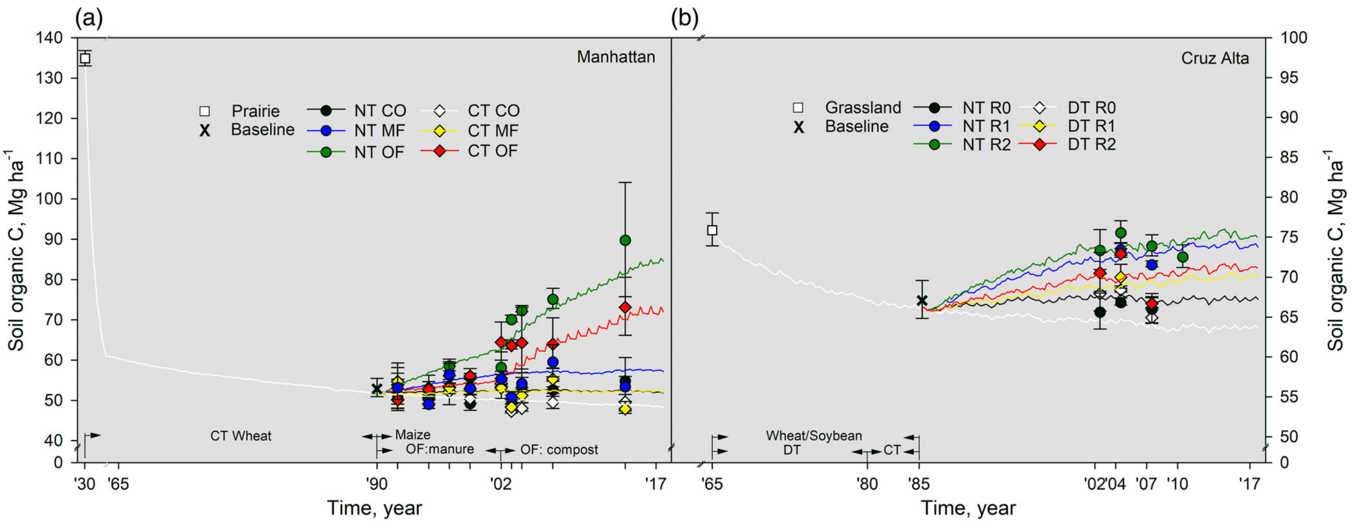

FIGURE 1 Soil organic carbon stocks as measured and simulated with the DSSAT-CENTURY model in the 0–30-cm soil layer of a Mollisol from Manhattan, KS, United States (a) and an Oxisol from Cruz Alta, RS, Brazil (b) according to soil tillage, fertilization and crop rotation practices. Error bars indicate the mean's standard errors. CO, control treatment without N; CT, chisel tillage; DT, disk tillage; MF, mineral fertilizers; NT, no tillage; OF, organic fertilizers; RO, wheat/soybean; R1, wheat/soybean/black oats/soybean; R2, wheat/soybean/black oats/soybean/black oats + vetch/maize/radish

TABLE 3 Crop stover biomass production as observed and simulated by the DSSAT model

Site: Manhattan, KS, United States (1990–2017).							
Crop		Chisel tillage			No-tillage		
		CO	MF	OF[a]	CO	MF	OF[a]
		Mg ha^{-1} year^{-1}					
Maize	Obs.	4.9 ± 2.5	7.1 ± 3.7	7.4 ± 4.1	4.1 ± 1.5	7.1 ± 3.3	7.1 ± 3.7
	Sim.	4.7 ± 0.6	7.3 ± 0.8	7.3 ± 0.8	4.1 ± 0.8	6.8 ± 0.7	7.4 ± 0.6
Site: Cruz Alta, RS, Brazil (1985–2017).							
Crop		Disk tillage			No-tillage		
		R0	R1	R2	R0	R1	R2
		Mg ha^{-1} year^{-1}					
Wheat	Obs.[b]	2.4 ± 0.7	3.4 ± 1.0	2.7 ± 0.7	2.7 ± 0.8	3.9 ± 0.9	3.1 ± 0.6
	Sim.	2.5 ± 0.9	3.4 ± 1.1	2.6 ± 1.0	2.8 ± 0.8	4.3 ± 1.7	3.6 ± 0.6
Soybean	Obs.	4.7 ± 1.8	4.4 ± 1.7	4.7 ± 1.9	5.1 ± 1.7	5.0 ± 1.6	5.2 ± 1.9
	Sim.[c]	5.3 ± 1.3	5.4 ± 1.3	5.7 ± 1.1	5.7 ± 1.1	6.0 ± 1.1	6.3 ± 0.8
Black oat	Obs.	-	4.7 ± 0.6	4.7 ± 0.1	-	5.7 ± 0.9	5.3 ± 0.7
	Sim.	-	4.5 ± 0.8	4.8 ± 1.0	-	4.5 ± 0.9	4.7 ± 1.0
Black oat + vetch	Obs.	-	-	5.1 ± 0.3	-	-	5.8 ± 0.5
	Sim.	-	-	5.7 ± 0.8	-	-	6.2 ± 0.8
Maize	Obs.	-	-	7.5 ± 3.1	-	-	9.4 ± 2.7
	Sim.	-	-	7.7 ± 2.0	-	-	9.1 ± 1.2
Radish	Obs.	-	-	2.9 ± n.a.	-	-	2.9 ± n.a.
	Sim.	-	-	2.8 ± 1.2	-	-	2.7 ± 1.2
Total	Obs.	7.1 ± 2.2	8.5 ± 1.7	10.4 ± 2.7	7.7 ± 2.0	9.8 ± 1.8	11.9 ± 2.7
	Sim.	7.8 ± 1.7	9.5 ± 1.8	10.5 ± 2.3	8.6 ± 1.5	10.3 ± 1.5	11.8 ± 2.4

[a] OF 1990–2001: cattle manure 3,000 Mg DM ha^{-1} (7% N, 7% lignin); OF 2002–2017: compost 13,000 Mg DM ha^{-1} (3% N, 30% lignin).

[b] Data from Cruz Alta as observed between 1985–2004 (Campos, 2006). The stover biomass of the grain crops was estimated with measured grain yield and a harvest index of 0.35 for soybean and 0.4 for maize and wheat.

[c] Simulated soybean stover biomass considering stover at harvest (stem, leaves and pods) and senesced dry matter added to the soil.

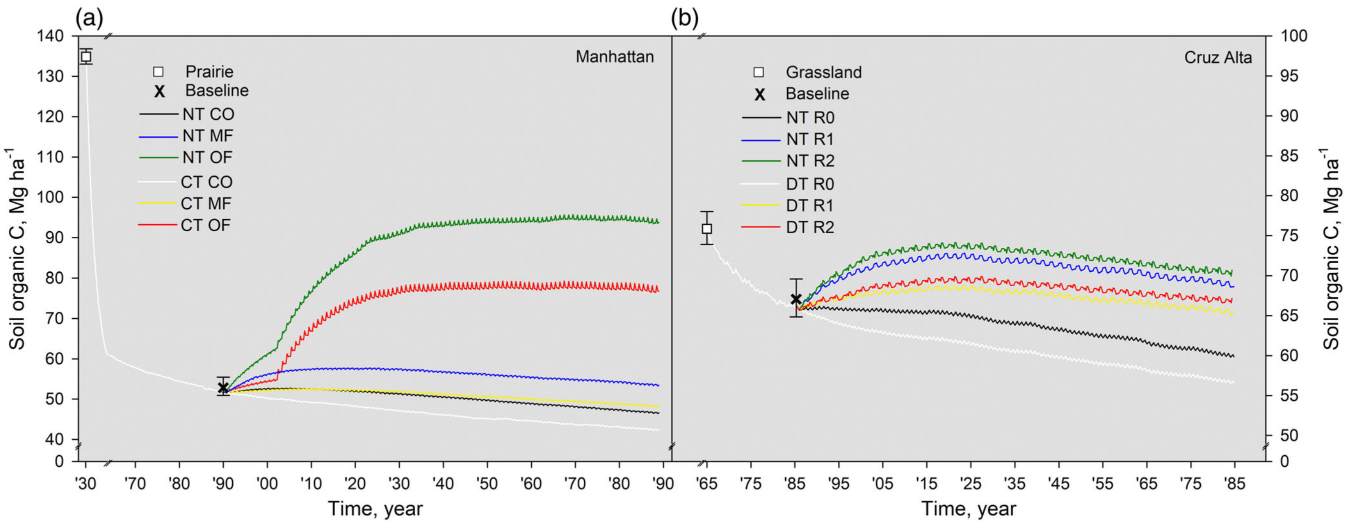

FIGURE 2 Long-term simulation of SOC stocks in the 0–30-cm soil layer of a Mollisol from Manhattan, KS, United States (a) and an Oxisol from Cruz Alta, RS, Brazil (b) according to soil tillage, fertilization and crop rotation practices. CO, control treatment without N; CT, chisel tillage; DT, disk tillage; MF, mineral fertilizers; NT, no tillage; OF, organic fertilizers; RO, wheat/soybean; R1, wheat/soybean/black oats (*Avena strigosa*)/soybean; R2, wheat/soybean/black oats/soybean/black oat + vetch (*Vicia sativa*)/maize (*Zea mays*)/radish (*Raphanus sativus*)

Oliveirade De Almeida MacHado, Inácio Fernandes Filho, & Lima Neves, 2004).

At the end of the pre-experimental period, simulated SOC was within the standard errors of measured baseline SOC at both sites. For the CT CO treatment in Manhattan, modelled SOC decreased from 52.2 to 48.6 Mg C ha^{-1} or −0.13 Mg C ha^{-1} $year^{-1}$ from 1990 to 2017 in the 0–30-cm soil layer (Figure 1a). During the same period, no significant changes in SOC were observed in CT MF and NT CO treatments. Simulated SOC stocks increased at 0.41 Mg C ha^{-1} $year^{-1}$ from 1990 to 2002 in the NT MF treatment, and then stabilized at 57.4 ± 0.3 Mg C ha^{-1} (mean ± standard deviation (SD)) until 2017. The application of cattle manure (3 Mg DM ha^{-1} $year^{-1}$, 7% lignin) increased modelled SOC linearly at 0.25 and 0.92 Mg C ha^{-1} $year^{-1}$ (1990–2002) in the CT OF and NT OF treatments, respectively. The application of composted organic waste (13 Mg DM ha^{-1} $year^{-1}$, 30% lignin) in the following period augmented SOC accrual asymptotically until 72.2 and 84.7 Mg C ha^{-1} in the same treatments (2002–2017). At Cruz Alta (Figure 1b), modelled SOC decreased from 66.4 to 63.9 Mg C ha^{-1} or −0.8 Mg C ha^{-1} $year^{-1}$ (1985–2017) in the 0–30-cm soil layer of the DT R0 treatment. Modelled SOC increased at 0.11 Mg C ha^{-1} $year^{-1}$ from 1985 to 1994 in the NT R0 treatment, which then stabilized at 67.4 ± 0.3 Mg C ha^{-1} until 2017. The adoption of R1 and R2 cropping systems with increased crop biomass inputs (Table 3) promoted SOC accrual regardless of tillage systems. The modelled SOC increased asymptotically to 70.2 and 71.2 Mg C ha^{-1} in 2017 with CT R1 and CT R2 treatments, and to 73.9 and 75.1 Mg C ha^{-1} in 2017 with NT R1 and NT R2 treatments, respectively. Although differences in modelled SOC accrual were negligible between R1 and R2 cropping systems under the same tillage system (~1.1 Mg C ha^{-1}), NT soils yielded a larger SOC recovery than DT soils (~3.8 Mg C ha^{-1}).

At both the Manhattan and Cruz Alta sites, SOC accrual peaked within the first 10 years after conversion of CT to NT and then stabilized after 10–17 years, as previously reported (Corbeels et al., 2016; West & Post, 2002). External C inputs from manure and compost applications at the Manhattan site significantly increased SOC stocks in both CT and NT soils. However, NT soils showed evidence of SOC saturation in the surface soil layer with partial translocation of SOC to underlying soil layers within 15 years after compost applications (Nicoloso et al., 2018). External C inputs did not show evidence to increase the duration of SOC accrual in NT soils. Simulations of long-term SOC dynamics (100 years after the beginning of experiments) were then performed using DSSAT weather generators for both sites (Figure 2). Soil organic C stock in the 0–30-cm layer of the CT CO treatment in Manhattan was predicted to decay until 42.7 Mg C ha^{-1} after 100 years of continuous maize without N fertilization (Figure 2a). The mean SOC loss rate predicted for the entire simulation period (−0.9 Mg C ha^{-1} $year^{-1}$) was similar to that observed during the experimental period (1990–2017). For the NT CO treatment, SOC stocks in the 0–30-cm soil layer remained stable during the first 28 years after conversion to NT (1990–2017). However, long-term simulations showed SOC decaying to 46.8 Mg C ha^{-1} in the same soil layer. Although modelled SOC stocks have increased in the 0–5-cm soil layer from 9.3 Mg C ha^{-1} and stabilized at 11.5 Mg C ha^{-1} under NT CO, SOC losses in 5–15 and 15–30-cm soil layers overcame the surface SOC accrual in the long term.

The application of mineral N (168 kg ha^{-1}) increased maize biomass production and SOC in both CT and NT soils (7.1 Mg ha^{-1}) in comparison with control treatments (4.1–4.9 Mg ha^{-1}) (Table 3). Nonetheless, SOC stocks (0–30 cm) in CT MF soil were predicted to decrease in the long term (100 years) to 48.4 Mg C ha^{-1}, although no significant changes were observed during the experimental period (1990–2017). Soil organic C losses for the CT MF treatment occurred in the 15–30-cm soil layer, whereas SOC stocks remained stable in both the 0–5 and 5–15-cm soil layers (data not shown). Similarly, SOC accrual observed during the experimental period (+5.7 Mg C ha^{-1}, stabilized at 16.0 Mg C ha^{-1}) for the NT MF treatment was mostly negated (72%) in the long term due to SOC losses in the 5–15 and 15–30-cm soil layers (−0.6 and −4.4 Mg C ha^{-1}). Thus, SOC stock (0–30 cm) for the NT MF treatment was predicted to return to levels (53.6 Mg C ha^{-1} after 100 years) similar to the baseline (52.1 Mg C ha^{-1}) but with greater SOC stratification from the surface to underlying soil layers (de Oliveira Ferreira et al., 2013). The use of OF had no impact on maize biomass production but increased both C and N inputs in comparison with other treatments. No-till soils had greater retention of C inputs as SOC than CT soils. Soil organic C stabilized at 77.9 ± 0.6 and 92.3 ± 0.6 Mg C ha^{-1} in the 0–30-cm soil layer of CT and NT soils, respectively. With external C inputs, SOC accrual in the 0–5 and 5–15-cm soil layers of both CT and NT soils overcame losses in the 15–30-cm soil layer (−3.0 and −3.3 Mg C ha^{-1}, respectively).

Stover biomass production was higher in Cruz Alta using double-cropping systems than in Manhattan with a single maize crop (Table 3). Nonetheless, long-term simulations showed decreasing SOC stocks from 66.4 to 56.8 and 60.0 Mg C ha^{-1} in the 0–30-cm soil layer of both DT and NT soils with wheat/soybean (R0) (Figure 2b). Soil organic C decreased in the 0–5, 5–15 and 15–30-cm layers of DT R0 treatment. For the NT R0 treatment, SOC accrual in the surface soil layer (12.9 to 14.7 Mg C ha^{-1}) did not compensate for SOC losses in underlying soil layers (−3.3 and −4.3 Mg C ha^{-1} in the 5–15 and 15–30-cm layers, respectively) predicted to occur during the simulated period (100 years). The intensification of crop rotations increased stover biomass inputs and initially augmented SOC stocks in both CT and DT soils. Nonetheless, SOC in DT soils was predicted to return to levels (65.4–67.4 Mg C ha^{-1} for R1 and R2, respectively) similar to the baseline due to SOC losses in the 15–30-cm soil layer. Long-term SOC losses in the 15–30-cm layer were partially negated by 69 and 48% of the SOC accrual in the surface layers of NT R1 and NT R2 treatments observed during the experimental period (1985–2017). Simulations showed SOC in NT R1 and NT R2 treatments (0–30 cm) decreasing from 73.9 and 75.1 Mg C ha^{-1} as modelled for 2017 to 68.8 and 70.8 Mg C ha^{-1} at the end of the simulation period (100 years), respectively.

The effect of stover biomass on SOC was mostly limited to the soil surface (0–5 cm) or to the underlying soil layer due to residue mixing with soil tillage (Franzluebbers, 2002). Thus, our study supports the notion that reduced soil disturbance, increased biomass production and external C inputs increase SOC stocks in the surface of agricultural soils (de Oliveira Ferreira, Amado, et al., 2018; Poulton et al., 2018). However, SOC accrual was limited to the first 15–20 years after the adoption of these soil, crop and fertilizer management practices. Furthermore, this effect was completely negated or at least partially offset due to long-term SOC losses in deeper soil layers, especially in tilled soils or agroecosystems with low to moderate biomass production. Previous studies already discussed the importance of the crop root system to maintain SOC at deeper soil layers (Baker, Ochsner, Venterea, & Griffis, 2007; McGowan, Nicoloso, Diop, Roozeboom, & Rice, 2019; Rumpel & Kögel-Knabner, 2011). However, roots of annual crops are mostly concentrated in the upper soil layers and may not compensate for SOC losses in deeper soil layers regardless of the soil tillage system (Olson, Al-Kaisi, Lal, & Lowery, 2014; Stewart et al., 2017). For instance, the root biomass of soybean, wheat and maize in the upper 10-cm depth accounted for 70, 76 and 79% of total root biomass measured to a depth of 50 cm of an Alfisol from central Missouri (Buyanovsky & Wagner, 1986). Similarly, the maize root biomass found in the 0–5 and 0–15-cm soil layers was reported to represent 82 and 89%, respectively, of the total biomass measured to 120-cm depth in a Mollisol under NT from central Kansas (McGowan, 2015). Although very few studies assessed root biomass of annual crops in tilled and NT soils, it is well known that soil physical and chemical attributes along with tillage and fertilization practices can affect both root biomass production and distribution throughout the soil profile (Anderson, 1988; Bolinder, Janzen, Gregorich, Angers, & VandenBygaart, 2007; Dalla Nora et al., 2017; Nicoloso et al., 2008; Qin, Stamp, & Richner, 2005), thus affecting SOC storage (de Oliveira Ferreira, Amado, et al., 2018; Ghimire, Machado, & Rhinhart, 2015; Olson et al., 2013; Stewart et al., 2017). The

TABLE 4 Simulated crop stover biomass by the DSSAT model with the adoption of best crop management practices (BP[a]), which consisted of the use of high-yield crop cultivars and higher maize plant density, increased and split N fertilization, and irrigation

Site: Manhattan, KS, United States (1990–2017).				
Crop	Chisel tillage		No-tillage	
	MF + BP	OF[b] + BP	MF + BP	OF[b] + BP
	Mg ha^{-1} year^{-1}			
Maize	14.9 ± 1.0	14.9 ± 1.0	14.7 ± 1.0	14.3 ± 1.6
Site: Cruz Alta, RS, Brazil (1985–2017).				
Crop	Disk tillage		No-tillage	
	R1 + BP	R2 + BP	R1 + BP	R2 + BP
	Mg ha^{-1} year^{-1}			
Wheat	5.0 ± 0.8	4.6 ± 0.9	5.0 ± 0.8	4.5 ± 0.9
Soybean	8.9 ± 0.3	8.9 ± 0.4	8.9 ± 0.3	8.9 ± 0.3
Black oat	4.3 ± 0.8	4.5 ± 0.6	4.3 ± 0.7	4.5 ± 0.9
Black oat + vetch	-	6.0 ± 1.1	-	6.0 ± 0.9
Maize	-	11.9 ± 1.1	-	12.4 ± 1.1
Radish	-	1.6 ± 0.6	-	1.8 ± 0.7
Total	13.6 ± 1.0	14.5 ± 1.8	13.6 ± 1.0	14.6 ± 2.1

[a] Crop cultivars, plant density and N fertilization are detailed in Tables S3 and S4.

[b] OF 1990–2001: cattle manure 3,000 Mg DM ha^{-1} (dry matter (DM), 7% N, 7% lignin); OF 2002–2089: compost 13,000 Mg DM ha^{-1} (3% N, 30% lignin).

adoption of best crop management practices (i.e., irrigation, optimization of N fertilization, high-yield crop cultivars and correction of soil acidity), agricultural intensification (i.e., high cropping frequency and cover crops) and the use of organic fertilizers can increase both stover and root biomass production and long-term SOC storage in NT soils (Dalla Nora et al., 2017; de Oliveira Ferreira, Amado, et al., 2018; Ogle et al., 2012; Poffenbarger et al., 2017; Poulton et al., 2018; Stewart et al., 2017).

3.3 | Scenarios with best crop management practices

Most long-term experiments assessing SOC storage according to tillage, cropping systems and fertilization practices are carried out simulating conventional crop management practices with crop yield and biomass production similar to regional averages (Bayer et al., 2006; Boddey et al., 2010; Corbeels et al., 2016; Follett et al., 2013; Martínez et al., 2016; Olson et al., 2013; Poffenbarger et al., 2017; Poirier et al., 2009; Stewart et al., 2017). Consequently, very few experiments were able to assess SOC dynamics in high-yield agroecosystems (Cook & Trlica, 2016; Grassini et al., 2015; Grassini & Cassman, 2012; Walia et al., 2017). Both experiments assessed in our study had environmental constraints (i.e., both rainfed with low annual precipitation in Manhattan and frequent summer droughts in Cruz Alta; Figure S1) and fertilization practices (i.e., low N input in Cruz Alta and single pre-plant N application in Manhattan) that may have limited crop biomass production, thus affecting long-term SOC storage at these sites (Grassini et al., 2015; Grassini & Cassman, 2012; Ogle et al., 2012; Poffenbarger et al., 2017). We tested alternative scenarios using the parameters calibrated in both experiments to simulate the effects of the adoption of BP on biomass production and long-term SOC storage based on selected treatments: CT MF, CT OF, NT MF and NT OF in Manhattan, and DT R1, DT R2, NT R1 and NT R2 in Cruz Alta.

The BP tested in these simulations were sprinkle irrigation (set automatically as required for grain crops by the DSSAT model), split and increased N fertilization (Table S4), and use of high biomass yield maize, wheat and soybean cultivars with increased plant density for maize (Table S3). The alternative scenarios with BP increased the simulated stover biomass production at both sites (Table 4). The stover biomass simulated for both sites using BP was within the range of aboveground maize, wheat and soybean biomass production in high-yield agroecosystems in the midwest United States and southern Brazil where BP were adopted (Dalla Nora et al., 2017; Grassini et al., 2011, 2015; Schwalbert et al., 2018).

Although the scenarios simulating the adoption of BP had higher stover biomass production in both CT and NT

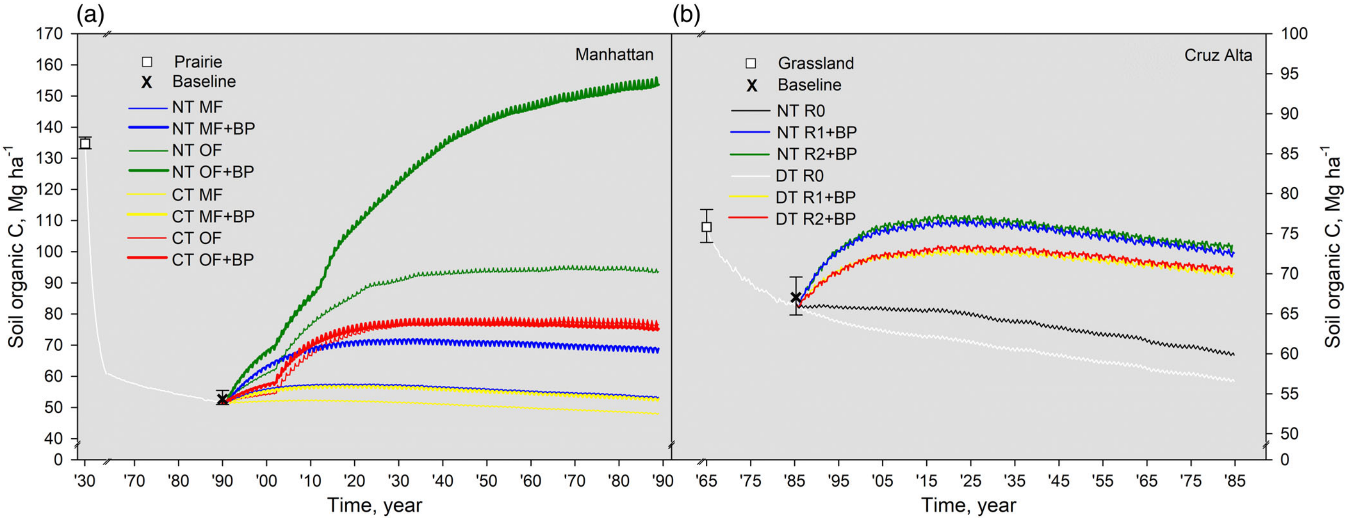

FIGURE 3 Long-term simulation of SOC stocks in the 0–30-cm soil layer of a Mollisol from Manhattan, KS, United States (a) and an Oxisol from Cruz Alta, RS, Brazil (b) according to soil tillage, fertilization, crop rotation, and the adoption of best crop management practices, which consisted of the use of high-yield crop cultivars and higher maize plant density, increased and split N fertilization, and irrigation. CO, control treatment without N; CT, chisel tillage; DT, disk tillage; MF, mineral fertilizers; NT, no tillage; OF, organic fertilizers; RO, wheat/soybean; R1, wheat/soybean/black oats/soybean; R2, wheat/soybean/black oats/soybean/black oat + vetch/maize/radish

soils in Manhattan, the effect on SOC storage was limited under CT (Figure 3a). The SOC dynamics simulated for the 0–30-cm layer of the CT MF + BP treatment followed a similar pattern to that observed in the NT MF but with redistribution of SOC between 0–5 and 5–15-cm soil layers due to residue mixing with tillage practices. In contrast to CT MF, SOC increased in the CT MF + BP treatment at 0.3 Mg C ha^{-1} year^{-1} during the first 15 years of our simulations until progressive SOC losses in the 15–30-cm soil layers decreased SOC back to levels similar to those at baseline (52.8 and 52.1 Mg C ha^{-1}, respectively). Nonetheless, SOC stocks in the CT MF + BP treatment at the end of our simulations was 4.4 Mg C ha^{-1} higher than in CT MF (48.4 Mg C ha^{-1}). For the CT OF + BP treatments, SOC accrual was faster than CT OF due to increased stover biomass input during the first 30 years of the simulation. However, SOC stocks stabilized at similar levels in both treatments (76.6 ± 0.9 and 77.9 ± 0.6 Mg C ha^{-1}, respectively). The higher N input (240 kg N ha^{-1} year^{-1}) simulated for the CT MF + BP treatment may have increased both litter and SOC mineralization (Grave et al., 2015; Poffenbarger et al., 2017), thus limiting the contribution of increased stover biomass inputs to long-term SOC storage in CT soil as compared with the composted organic waste (OF). Composted organic waste typically has a high lignin content of 20–40% (Francou, Linères, Derenne, Le Villio-Poitrenaud, & Houot, 2008), presenting low mineralization rates and promoting higher recovery of C inputs as SOC than crop biomass regardless of soil tillage (Biala, 2011; Grave et al., 2015; Lynch, Voroney, & Warman, 2006).

The use of BP increased both SOC accrual and long-term SOC storage in NT soils from Manhattan. In the NT MF + BP treatment, SOC increased at 1.2 Mg C ha^{-1} year^{-1} during the first 15 years of our simulation. Soil organic C accrual simulated for both 0–5 and 5–15-cm soil layers (+17.8 and +2.1 Mg C ha^{-1}, respectively) compensated for SOC losses in the 15–30-cm layer (−3.9 Mg C ha^{-1}) as predicted throughout the simulated period for the NT MF + BP treatment. Thus after 100 years, SOC in the 0–30-cm layer of the NT MF + BP treatment was 16 Mg C ha^{-1} higher than the baseline (68.1 and 52.1 Mg C ha^{-1}, respectively). For the NT OF + BP treatment, SOC was predicted to increase up to 152.7 Mg C ha^{-1} in the 0–30-cm soil layer, surpassing SOC levels observed in the prairie soils (135 Mg C ha^{-1}). Soil organic C accrual was simulated to occur in both 0–5 and 5–15-cm soil layers (+33.6 and +69.9 Mg C ha^{-1}, respectively), whereas for the 15–30-cm soil layer, SOC losses also decreased in comparison to the other simulated scenarios (−2.5 Mg C ha^{-1}).

The simulations with BP in Cruz Alta also showed higher SOC accrual in both DT and NT soils (Figure 3b). Nonetheless, differences in SOC between R1 and R2 decreased within the same tillage system because annual biomass production was similar for R1 and R2 cropping systems with the adoption of BP (Table 4). Previous studies already suggested that increased crop diversity favours SOC storage in NT soils (Alhameid, Ibrahim, Kumar, Sexton, & Schumacher, 2017; de Oliveira Ferreira et al., 2013, 2016; de Oliveira Ferreira, Amado, et al., 2018). However, opposite or null results were reported elsewhere (Luo et al., 2010; Wang, Butterly, Baldock, & Tang, 2017). Our results suggest that increased biomass production, rather than the number of different crops within a cropping system (i.e., crop diversity), is crucial for long-term SOC storage as simulated for high-yield agroecosystems with BP. However, the inclusion of maize and cover crops favoured SOC storage in both DT and NT soils in low- to moderate-yield treatments with lower crop diversity and higher soybean frequency (de Oliveira Ferreira et al., 2013, 2016). Thus, SOC accrual in the 0–30-cm layer of DT R1 + BP and DT R2 + BP treatments averaged 0.3 Mg C ha^{-1} $year^{-1}$ during the first 20 years of our simulation. For the NT soils, SOC accrual rates in R1 + BP and R2 + BP treatments were 50% higher (0.45 Mg C ha^{-1} $year^{-1}$) during the same period in comparison with DT soils. Soil organic C stocks in the DT R1 + BP, DT R2 + BP, NT R1 + BP and NT R2 + BP treatments increased up to 72.9, 73.4, 76.5 and 77.1 Mg C ha^{-1} but decreased to 70.1, 70.9, 72.7 and 73.7 Mg C ha^{-1}, respectively, at the end of the simulated period due to SOC losses in the 15–30-cm layer. For comparison, SOC observed in the grassland soil in Cruz Alta was 75.2 Mg C ha^{-1}.

Our simulations showed a higher potential for SOC sequestration regarding both SOC accrual rates and total SOC storage in temperate than in warmer agroecosystems (Corbeels et al., 2016). Nonetheless, our results also confirm that long-term NT, BP with increased C inputs in high-yield fields and organic fertilization should be further promoted to increase SOC storage in both tropical and temperate agroecosystems (Boddey et al., 2010; Poffenbarger et al., 2017; Poulton et al., 2018). The integration of these practices could ultimately restore SOC to the levels of prairie and grassland soils (de Oliveira Ferreira et al., 2016; de Oliveira Ferreira, de Moraes Sá, et al., 2018), which would help with the amelioration of agricultural soils with regards to soil quality and productivity and with the mitigation of climate change (Jat et al., 2014; Minasny et al., 2017). Furthermore, complementary strategies (e.g., crops with deeper and profuse root systems, alleviation of subsoil acidity, etc.) (Dalla Nora et al., 2017; de Oliveira Ferreira et al., 2018, b) should be implemented to increase root biomass inputs to deeper soil layers, thus sustaining SOC levels in the long term.

4 | CONCLUSIONS

We used the DSSAT-CENTURY model to simulate SOC dynamics in two long-term experiments assessing soil tillage, nitrogen sources and cropping systems in the midwest of the United States and southern Brazil. The model overestimated SOC storage in tilled soils from both experiments, requiring modifications of default values for litter C respiration losses. Modifications of C respiration losses yielded an excellent agreement between modelled and observed SOC stocks in tilled soils. No parametrization of default values was necessary for NT soils. Cultivation of prairie and grassland soils led to a decrease of SOC stocks, which were partially recovered with decreasing soil disturbance (NT) or increasing C inputs as a response to N fertilization, intensification of cropping systems and organic amendments. However, long-term simulations (100 years) revealed that SOC losses in the 15–30-cm layer could partially offset SOC accrual in the surface layers (0–5 and 5–15 cm). Alternative scenarios simulated with the adoption of BP (i.e., irrigation, high-yield cultivars, increased plant density and split and increased N fertilization) showed a greater potential for SOC accrual in NT soils, ultimately recovering SOC up to the original levels of prairie and grassland soils. Our results suggest that the adoption of conservation agriculture, recycling of organic fertilizers and the use of BP should be further promoted for amelioration of agricultural soils with regards to soil carbon sequestration and permanence.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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