Predicting soil C changes over sugarcane expansion in Brazil using the DayCent model

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Abstract

In recent years, the increase in Brazilian ethanol production has been based on expansion of sugarcane-cropped area, mainly by the land use change (LUC) pasture–sugarcane. However, second-generation (2G) cellulosic-derived ethanol supplies are likely to increase dramatically in the next years in Brazil. Both these management changes potentially affect soil C (SOC) changes and may have a significant impact on the greenhouse gases balance of Brazilian ethanol. To evaluate these impacts, we used the DayCent model to predict the influence of the LUC native vegetation (NV)–pasture (PA)–sugarcane (SG), as well as to evaluate the effect of different management practices (straw removal, no-tillage, and application of organic amendments) on long-term SOC changes in sugarcane areas in Brazil. The DayCent model estimated that the conversion of NV-PA caused SOC losses of 0.34 ± 0.03 Mg ha⁻¹ yr⁻¹, while the conversion PA-SG resulted in SOC gains of 0.16 ± 0.04 Mg ha⁻¹ yr⁻¹. Moreover, simulations showed SOC losses of 0.19 ± 0.04 Mg ha⁻¹ yr⁻¹ in SG areas in Brazil with straw removal. However, our analysis suggested that adoption of some best management practices can mitigate these losses, highlighting the application of organic amendments (+0.14 ± 0.03 Mg C ha⁻¹ yr⁻¹). Based on the commitments made by Brazilian government in the UNFCCC, we estimated the ethanol production needed to meet the domestic demand by 2030. If the increase in ethanol production was based on the expansion of sugarcane area on degraded pasture land, the model predicted a SOC accretion of 144 Tg from 2020 to 2050, while increased ethanol production based on straw removal as a cellulosic feedstock was predicted to decrease SOC by 50 Tg over the same 30-year period.

Keywords: best management practices, biofuels, land use change, second-generation ethanol, soil organic matter, straw removal

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Introduction

Bioenergy is critical for environmental security and climate change mitigation. Future projections suggest that 30% of the world’s fuel supply might be bio-based by 2050 (Macedo et al., 2015). However, the C balance in the agricultural phase still raises uncertainties about the environmental feasibility of biofuels expansion. Land use change (LUC) due to biofuel crop establishment may be associated with soil C (SOC) losses that negatively impact the biofuel’s greenhouse gases (GHG) balance (Fargione et al., 2008; Mello et al., 2014). The relevance of LUC has been emphasized by several authors, especially in relation to political decisions made for increasing biofuel production (Lapola et al., 2010; Hudiburg et al., 2016).

In Brazil, the negative effects of LUC brought out concerns about the efficiency of the sugarcane ethanol as a climate change mitigation option (Fargione et al., 2008; Lapola et al., 2010). However, sugarcane ethanol shows the largest average net GHG mitigation (including LUC effects) compared to other first-generation ethanol feedstocks (Renouf et al., 2008). Nowadays, Brazil is considered to have developed the world’s first sustainable biofuel economy and in many respects is the biofuel industry leader (Souza et al., 2014). This reputation is largely based on its sugarcane industry.

Between 2004 and 2012, Brazil’s GDP increased by 32% (IPEA, 2016), while GHG emissions decreased by 52% (MCTI, 2014), breaking the link between economic growth and GHG emissions. Despite these advances, the Brazilian government announced ambitious goals in the last UNFCCC: reduce GHG emissions by 43% below 2005 levels by 2030 (NDC Brazil, 2015). To do so, among other strategies, the government established that...
the sugarcane contribution to the energy supply in Brazil by 2030 must be around 16%. Meeting this mandate probably will require a substantial increase in sugarcane production area.

Previous studies using the Century model evaluated the effects of green harvest management (GM – harvest without burning) and organic amendments on SOC changes in sugarcane areas in Brazil (Galdos et al., 2009; Brandani et al., 2015). As concluded by these studies, the high crop residue inputs in areas under GM is the main factor associated with increments on SOC in sugarcane areas in Brazil. However, the sugarcane residues have become an attractive source of biomass for bioelectricity and second-generation (2G) ethanol production in Brazil (Walter & Ensinas, 2010). Crop residue removal is associated with decreases on SOC (Wilhelm et al., 2007; Wortmann et al., 2010), but the adoption of some best management practices can mitigate these losses (Paustian et al., 2016).

In recent years, almost all the sugarcane expansion in Brazil has been done under pasture areas (Dias et al., 2016). Using the Century model, Silva-Olaya et al. (2016) studied the impact of LUC from native vegetation and pasture to sugarcane cultivation on SOC dynamics in Brazil. The site-level data used in Silva-Olaya et al. (2016) were those reported by Mello et al. (2014), where most of sugarcane areas were either still harvested with burning or this practice had just been stopped for 3 years or less before the sampling time. In this sense, the longer term effects of the conversion pasture–sugarcane on SOC remain unclear for areas under GM. Moreover, there are not published papers on the effects of straw removal on SOC in sugarcane areas in Brazil. Simulation models provide a feasible and cost-effective option to predict the long-term potential impacts of LUC and management practices on SOC. Furthermore, predictions on SOC changes are a useful tool to encourage decision makers and planners to develop sustainable land use strategies and soil management systems in areas to biofuel production (Campbell & Paustian, 2015). In this study, we used the DayCent model to predict the impact of unburnt sugarcane expansion into pasture areas, as well as to evaluate the effect of different management practices, such as straw removal, no-tillage, and application of organic amendments (vinyasse and filter cake), on long-term SOC changes in sugarcane areas in Brazil.

**Materials and methods**

**Description of study sites**

For the field data used in this research (Cherubin et al., 2015; Oliveira et al., 2016b), we sampled three land uses – native vegetation (NV), pasture (PA) and sugarcane (SG) – at sites across south-central Brazil, the largest sugarcane region in the world, accounting for 93.4% of Brazilian ethanol production (UNICA, 2015). The climate at all the sites has rainfall concentrated in the spring and summer (October–April), while the dry season is in the autumn and winter (May–September). The soils are typical of the Brazilian tropical region, well-drained and highly weathered, with a predominance of kaolinite, Fe oxides (goethite and hematite), and Al oxide (gibbsite) in the clay-size fraction.

The first site, Lat_17S, is located in Jataí, southwestern region of Goiás state (Lat.: 17°56’16″ S; Long.: 51°38’31″ W) with a mean altitude of 800 m and a predominance of clayey Acrudox soils (USDA, 2014). The climate classification is Aw type (Köppen) mesothermal tropical, with a mean annual temperature of 24.0 ℃ and an annual precipitation of 1600 mm. The second site, Lat_21S, is located in Valparaíso, west region of São Paulo state (Lat.: 21°14’48″ S; Long.: 50°47’04″ W) with a mean altitude of 425 m and predominance of loamy Hapludalf soils (USDA, 2014). The climate classification is Cwa type (Köppen) humid tropical. The area has a mean annual temperature of 23.4 ℃ and an annual precipitation of 1240 mm. The third site, Lat_23S, is located in Ipaussu, south-central region of the São Paulo state (Lat.: 23°05’08″ S; Long.: 49°37’52″ W), with a mean altitude of 630 m and predominance of clayey Hapludox soils (USDA, 2014). The climate classification is Cw type (Köppen) tropical. The annual mean temperature is 21.7 ℃, and the annual precipitation is 1470 mm. A general description of each land use is shown in Fig. 1. For more information about soil parent material and soil classification, LUC sequence, sampling, and laboratory procedures, see Cherubin et al. (2015), Oliveira et al. (2016a,b).

**The DayCent Model**

We used the most recent version of DayCent model (DD14-centEvI) to simulate changes in soil organic matter (SOM) dynamics in areas under LUC to sugarcane expansion in Brazil. DayCent (Parton et al., 1998; Del Grosso et al., 2001) is a modified, daily time step version of the biogeochemical ecosystem Century model (Parton et al., 1987). Both Century and DayCent simulates fluxes of C and N between the atmosphere, vegetation, and soil, including the dynamics of multiple C and N soil organic matter pools, but DayCent also includes other processes such as greenhouse gases emissions.

In DayCent, phenology, net primary productivity, shoot:root ratio, and the C:N ratio of biomass in plant components are species-specific. Moreover, the model calculates potential plant growth as a function of water, light, and soil temperature and limits actual plant growth based on specific plant nutrient requirements. The type and timing of each management event can be specified, including tillage, fertilization, organic matter addition, harvest, burning, and grazing intensity. Litter decomposition and SOM turnover are determined by the amount and quality of residue returned to the soil, the size of the SOM pools, and temperature and water controls (Del Grosso et al., 2001). These aspects allow DayCent to generate accurate simulations for multiple vegetation types under a wide range of management practices at diverse sites, which make the model particularly useful for simulating land use change.
Accordingly, DayCent has been used and validated across a range of land use and management scenarios (Del Grosso et al., 2009; Duval et al., 2013; Hudiburg et al., 2016). The Century model was widely used for simulations in pastures (Cerri et al., 2004, 2007) and sugarcane areas (Galdos et al., 2009, 2010; Brandani et al., 2015; Silva-Olaya et al., 2016) in Brazil. However, there is no published research using the DayCent model for simulations in Brazil so far.

**Modeling procedures**

The DayCent model requires input of climate and soil data. In this study, we used climate data (daily maximum and minimum average temperature and precipitation) from 1901 to 2015, provided by MsTMIP (Wei et al., 2014). We opted to use this gridded global product because is the only long-term and daily weather data available for these sites. Others weather data available for Brazil (e.g., INMET, Cepagri) were restricted to more recent periods or in a monthly basis. The site-specific soil attributes used to the initialization of the model are available in Cherubin et al. (2015).

To initialize the model prior to simulating forest clearing and pasture establishment, we used the forest submodel to estimate equilibrium SOM levels and plant productivity under native forest conditions, over a 7000-year simulation period. Two kinds of native vegetation were simulated using the parameterization developed by Silva-Olaya et al. (2016): Cerrado Forest (Lat_17S) and Atlantic Forest (Lat_21S and Lat_23S; Fig. 1). In our simulations, the main difference between these forest types is the N input by biological fixation in Cerrado Forest (Bustamante et al., 2012). The disturbances on these areas were fire events and tree mortality (Cerri et al., 2004). After simulating the equilibrium condition in native vegetation, the model was set to simulate the deforestation process following the slash-and-burn procedure. Those events were parameterized using similar calibration procedures as those developed by Cerri et al. (2004) for the Century model.

As for most pastures in Brazil, the pastures evaluated in our assessment are to some degree degraded and do not achieve the level of productivity characteristic of well-managed pastures. To simulate this condition, we adjusted the potential aboveground production, based on the biomass production for degraded pastures in Brazil reported by Lilienfein & Wilcke (2003). Regarding the grazing management, as the areas presented different stocking rates (Fig. 1), we specified different levels of grazing according to the options currently available in the model. We assumed continuous grazing through all the year, including the dry season period.

The simulations for sugarcane areas were performed using parameterization for the sugarcane crop developed by Galdos et al. (2009, 2010), Campbell (2015), and Silva-Olaya et al. (2016). The potential biomass production was adjusted to match the field data for south-central Brazil (UNICA, 2015), assuming the biomass partitioning develop for sugarcane by Galdos et al. (2010). Sugarcane renovation was performed every 6 years, and the tillage operations (plowing, disking, and subsoiling) were simulated using the intensive default tillage parameters specified at the model. Organic amendments (vinasse and filter cake) are currently applied on two of our sites (Lat_21S and Lat_23S). The composition of the filter cake used in this study was 228 g C kg⁻¹, 12 g N kg⁻¹ and 160 g lignin kg⁻¹ (Galdos et al., 2009). The composition of vinasse used was based on the analysis reported by Prado et al. (2013), with 11.56 g C L⁻¹ and 0.42 g N L⁻¹.

Currently, all the sites evaluated are under GM. However, in Lat_23S, the sugarcane was harvested with burning during a 13-year period (Fig. 1). In this specific case, we used the parameters for burning events developed by Galdos et al. (2009), in which 85% of the dry matter of the trash (leaves and tops) is removed by the fire, and 80% of the N in the residue material is lost to the atmosphere. For the GM, the model was set to remove 99% of aboveground biomass, with 94% of dry matter in tops and leaves and 1% of stalks returned to the system as litter after the harvest (rates reported by mills in Brazil).

**Model outputs and statistical analysis**

Usually, DayCent model is set up for simulations of SOM dynamics in the top 0.2 m soil depth (Parton et al., 1998). For this study, DayCent was parameterized to simulate SOM dynamics to a depth of 0.3 m, by decreasing the decay rate of all SOM pools by 15% (W. Parton and M. Hartman, pers.)

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**Fig. 1** Land use transitions and brief description of the management practices of studied sites in south-central Brazil and future scenarios to sugarcane cultivation in Brazil. AU, animal units; Fert, fertilizers applied; PA-SG, pasture to sugarcane land use conversion; Stalk yd, stalk yield.
comm.). Simulation output variables evaluated were total soil C and N stocks, and natural isotopic abundance of $^{13}$C. The proportion of soil C derived from native vegetation (native-C) or from pasture and sugarcane (modern-C) was calculated with the equations for soil C-partitioning proposed by Bernoux et al. (1998) using the simulated $\delta^{13}$C values. The rates of soil C change associated with land use/management shifts are the average of the three sites ($n = 3$).

Statistical analyses of model results were performed in accordance with tests proposed by Smith et al. (1997) to assess goodness-of-fit of the DayCent model to the measured C stocks, N stocks, and soil C-partitioning. The statistical metrics were as follows: correlation coefficient ($r$), root mean square error (RMSE), mean difference (M), relative error (E), and lack of fit (LOFIT).

**Future scenarios**

Based on feasible management strategies for future sugarcane cultivation in Brazil, we simulated the soil C changes in areas of sugarcane under five management scenarios:

- Scenario I: green management, without burning or straw removal (GM)
- Scenario II: Straw removal
- Scenario III: Straw removal with no-tillage
- Scenario IV: Straw removal with organic amendments
- Scenario V: Straw removal with no-tillage and organic amendments

We assumed a maximum rate of 75% of straw removal for sugarcane areas in Brazil, as reported by Cardoso et al. (2013). No-tillage operations were simulated using the default files available in the DayCent model. The organic amendments were vinasse and filter cake, applied in rates commonly used in sugarcane areas in Brazil, that is, 200 m$^3$ ha$^{-1}$ yr$^{-1}$ and 25 Mg ha$^{-1}$ yr$^{-1}$, respectively (Prado et al., 2013). Moreover, based on the commitments made by Brazilian government in the UNFCCC (iNDC Brazil, 2015), we estimated the sugarcane area expansion according to the projected increased ethanol production needed to meet the domestic demand by 2030 in two scenarios: with and without the contribution of 2G technologies to ethanol production. To reach the estimated production of ethanol in 2030, we assumed linear rates of increment in planted area. Using these two scenarios of expansion and the simulated rates of soil C change under different management practices, we estimated soil C changes in sugarcane areas in Brazil over the next decades, without assuming any biophysical or economic basis for expansion allocation across south-central Brazil.

**Results**

**Model performance**

The DayCent model estimates were consistent with the field-observed SOM changes in areas undergoing LUC for sugarcane expansion in Brazil (Table 1, Fig. 2). The measured and simulated SOC were well correlated ($r = 0.98; P < 0.05$), with the model underestimating the SOC by $2.1 \pm 4.6$, $4.8 \pm 1.3$, and $2.7 \pm 8.6\%$ in NV, PA, and SG areas, respectively (Table 1). Despite the correlation between the measured and simulated values ($r = 0.91; P < 0.05$), the model showed a tendency to overestimate the N stocks in these areas, with values $23.4 \pm 18.2\%$ greater than the measured N stocks in PA and SG areas (Table 1, Fig. 2). The DayCent model also accurately simulated our measured results for C-partitioning, with simulated soil native-C underestimated by $7.7 \pm 2.1\%$ and the simulated soil modern-C $9.7 \pm 19.7\%$ greater than the measured values.

Goodness-of-fit measures show that the DayCent model represented well the changes of SOM for the NV-PA-SG conversions evaluated. With exception of the N stocks, values for RMSE indicated a small difference between measured and simulated values (Table 2). Values for M and E showed an absence of significant bias in the simulated soil C and N stocks, and C-partitioning. However, LOFIT pointed to lack of fit between the measured and simulated N stocks and soil C-partitioning (Table 2).

**Long-term SOC changes undergoing NV-PA-SG conversions in Brazil**

The DayCent model estimated that the conversion of NV-PA is associated with SOC losses of $0.34 \pm 0.03$ Mg C ha$^{-1}$ yr$^{-1}$ in areas of south-central Brazil (Fig. 3). After the conversion of these pastures to sugarcane under GM, we observed the partial recovery of the SOC, at a rate of $0.16 \pm 0.04$ Mg C ha$^{-1}$ yr$^{-1}$. We did not include the SOC changes for Lat_23S between 1990 and 2003, when the sugarcane was harvested with burning (Fig. 1). In this case, the SOC losses simulated by the DayCent model were $1.04$ Mg C ha$^{-1}$ yr$^{-1}$ (Fig. 3c). Moreover, the simulated SOC losses in the year right after sugarcane crop renovation were $1.14 \pm 0.46$ Mg C ha$^{-1}$ (Fig. 3). Normalizing the SOC values relative to those under native vegetation (NV=100) at each site, we observed that the simulated SOC changes after LUC showed a very similar pattern across sites, with a consistent SOC loss after the LUC NV-PA and SOC increases within the transition PA-SG (Fig. 3d). By 2050, under the current management practices, the SOC in SG areas was predicted to be $86.1 \pm 2.8\%$ of those observed in NV.

The C-partitioning using the simulated $\delta^{13}$C values of SOM also showed a clear pattern in areas undergoing the LUC NV to PA to SG in Brazil (Fig. 3). In PA areas, native-C losses were $0.93 \pm 0.41$ Mg C ha$^{-1}$ yr$^{-1}$, coupled with modern-C gains of $0.48 \pm 0.20$ Mg C ha$^{-1}$ yr$^{-1}$. For SG, native-C losses and modern-C increases were $0.39 \pm 0.17$ and $0.56 \pm 0.22$ Mg C ha$^{-1}$ yr$^{-1}$, respectively (Fig. 3).
Predicted effects of straw removal on SOC in sugarcane areas in Brazil

Straw management is a major issue affecting long-term SOC maintenance under sugarcane in Brazil (Fig. 4). The DayCent model suggested that GM would promote increased SOC, while straw removal can notably reduce SOC in sugarcane areas (Fig. 4). However, adoption of best management practices can mitigate the negative effects of straw removal, highlighting the application of organic amendments, which in our simulations showed similar results to areas under GM (Fig. 4).

The implementation of 2G technologies in Brazil will drastically alter the land demand for sugarcane

|                | Measured | Simulated |
|----------------|----------|-----------|
| Soil C stocks (Mg ha⁻¹) |          |           |
| Lat_17S NV     | 49.1 ± 3.5* | 50.9      |
| Lat_17S PA     | 37.2 ± 3.2  | 38.7      |
| Lat_17S SG     | 38.2 ± 2.1  | 39.0      |
| Lat_21S NV     | 48.6 ± 3.2  | 47.4      |
| Lat_21S PA     | 37.2 ± 2.8  | 36.5      |
| Lat_21S SG     | 40.1 ± 3.1  | 37.5      |
| Lat_23S NV     | 89.9 ± 8.5  | 86.2      |
| Lat_23S PA     | 76.9 ± 6.7  | 74.2      |
| Lat_23S SG     | 60.5 ± 4.2  | 68.5      |

*Standard deviation from the mean values (n = 9).
production in the next decades. Without 2G ethanol contribution, we estimated an expansion of sugarcane planted area of 56.4% to meet the domestic ethanol demand by 2030, based on the commitments made by Brazilian government in the UNFCCC (INDC Brazil, 2015). The contribution of 2G technologies can notably decrease the land demand for sugarcane ethanol production (Table 3). However, estimated SOC changes in a scenario where the increase in ethanol production is based on the expansion of sugarcane onto pastures areas pointed to gains in C-savings of Brazilian ethanol, while the straw removal can affect negatively the C balance by decreasing the SOC in 50 Tg between 2020 and 2050 in sugarcane areas in Brazil (Table 3).

Discussion

The DayCent model reliably reflected the main trends of SOC changes undergoing the LUC NV-PA-SG in our sites. Using the Century model, Galdos et al. (2009), Brandani et al. (2015), and Silva-Olaya et al. (2016) successfully simulated SOC changes in sugarcane areas in Brazil. Moreover, Duval et al. (2013) concluded that the DayCent model performed well for simulating SOC changes undergoing the conversion pasture-energy cane in USA.

Despite the absence of significant bias (Table 2), the model appeared to overestimate N stocks, mainly in PA and SG areas (Table 1). Conant et al. (2005) observed that the DayCent model overestimated N stocks for half of pastures evaluated in sites from USA, UK, and Canada. However, due to the rapid N transformations in a warm and humid environment, we must take into account the possibility of N losses during the sampling, transport, and initial processing of the soil samples, which could have contributed to the discrepancies between measured and modeled soil N stocks in our study.

For the C-partitioning, some lack of fit between the measured and simulated values were observed (Table 2), mainly related with the disagreement between the measured and simulated modern-C stocks in SG areas from Lat_23S (Table 1). At this site, sugarcane was harvested with burning between 1990 and 2003 (Fig. 1). Burning events cause shifts in δ¹³C values of C4-derived charcoal (Krull et al., 2003), which certainly interfere in the C-partitioning. Effects of pyrogenic C on estimates of SOM partitioning is not accounted for in the DayCent model estimates. Nevertheless, the RMSE values indicated that the simulated C-partitioning still fell within the 95% confidence interval for the whole dataset (Table 2).

Overall, despite the disagreements discussed above, our DayCent simulations matched the direction of the main SOM shifts undergoing the LUC NV-PA-SG for all sites evaluated, even for N stocks and C-partitioning. Smith et al. (2012) showed that widely used process-based models (including Century) simulated values in the same uncertainty range as estimates derived from field experiments in areas for biofuels production. Moreover, DayCent is the most comprehensive of the process-based models when it comes to C dynamics representing plant and soil interactions (Robertson et al., 2015).

DayCent model predicted SOC losses of 0.34 ± 0.03 Mg C ha⁻¹ yr⁻¹ in the transition NV-PA (Fig. 3). Assessing SOC changes associated with the LUC NV-PA in Brazil, Maia et al. (2009) and Franco et al. (2015) found losses of SOC at rates of 0.28 and 0.40 Mg ha⁻¹ yr⁻¹, respectively. These SOC losses can

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Table 2  Statistical tests applied for the validation between measured and simulated values of soil C and N stocks and C-partitioning (native-C and modern-C) of areas under native vegetation, pasture and sugarcane cropping in south-central Brazil

| Statistical test | Soil C stocks | Soil N stocks | Native-C stocks | Modern-C stocks |
|-----------------|---------------|---------------|-----------------|-----------------|
| r = Correlation Coefficient | 0.98          | 0.91          | 0.99            | 0.94            |
| \( F = \left( \frac{n-2}{\hat{r}} \right)^2 / (1-r^2) \) | 509.97        | 39.17         | 351.00          | 28.06           |
| F-value at \( P = 0.05 \) | 5.59          | 5.59          | 7.71            | 7.71            |
| RMSE = Root mean squared error of model | 4.17%         | 23.73%        | 8.81%           | 15.27%          |
| RMSE (95% Confidence Limit) | 10.36%        | 16.17%        | 9.99%           | 12.95%          |
| M = Mean Difference | 0.95          | −0.57         | 2.93            | −0.86           |
| t = Student’s t of M | 1.31          | 1.97          | 5.92            | 0.96            |
| t-value (Critical at 2.5% – Two-tailed) | 2.36          | 2.36          | 2.78            | 2.78            |
| E = Relative Error | 1.74          | −14.02        | 8.04            | −6.11           |
| E (95% Confidence Limit). = +/− | 9.63          | 15.17         | 9.23            | 11.72           |
| LOFIT = Lack of Fit | 418.85        | 74.48         | 555.47          | 252.24          |
| F = MSLOFIT/MSE* | 2.17          | 29.60         | 11.56           | 15.95           |
| F (Critical at 5%) | 2.19          | 2.19          | 2.65            | 2.65            |

*MS, mean squared; MSE, mean squared error.
be attributed to both deforestation and biomass burning effects, and subsequent processes of soil degradation in pasture areas (Maia et al., 2009). After the LUC PA-SG (under GM), the simulations showed increments on SOC at a rate of 0.16 ± 0.04 Mg C ha⁻¹ yr⁻¹ until 2050. This result matched the previous rate (0.12 ± 0.03 Mg ha⁻¹ yr⁻¹) obtained in our field-scale assessment (Oliveira et al., 2016b). In USA, positive SOC changes were predicted when pastures were converted to energy cane (Duval et al., 2013) or Miscanthus production (Dunn et al., 2013). Moreover, Galdos et al. (2009) projected SOC gains of 0.23 Mg ha⁻¹ yr⁻¹ in Century simulations for SG areas under GM in Brazil.

The overall trend of increase in SOC in areas under GM is mainly related to the large input of organic material by sugarcane crop residues. In our study, the simulated C-partitioning suggested that the high input of crop residues in SG areas under GM is associated with a positive C balance, with the losses of native-C lower than the gains of modern-C, the opposite of PA areas.

In Lat_23S, when the SG was harvest with burning (1990–2003), a drop in SOC was observed (Fig. 3), as reported in other simulation studies (Galdos et al., 2009; Brandani et al., 2015). As a consequence, the conversion PA-SG with preharvest burning is associated with SOC losses (Mello et al., 2014). However, nowadays almost all SG plantations in Brazil are green harvested (UNICA, 2015).

Sugarcane is usually replanted every sixth year. Under conventional tillage, the whole replant area is disturbed using plowing, diskng, and, commonly, subsoiling. Our simulations showed that tillage operations caused a SOC loss of 1.14 ± 0.42 Mg ha⁻¹ in the year right after sugarcane replanting, in agreement with previous studies in Brazil (Silva-Olaya et al., 2013; Figueiredo et al., 2015). The C-partitioning showed that most of the C from sugarcane (modern-C) from the previous five-year production period can be lost during the replanting period (Fig. 3). Such SOC losses are comparable with the GHG emissions from sugarcane burning.
et al. associated with potential environmental impacts, high-straw removal (Fig. 4). The harvest of crop residues is to other regions, increasing deforestation (Lapola consequences of such LUC is the migration of livestock of natural vegetation to pastures. One of the potential partially offset the C debt resulting from the conversion with sugarcane is associated with SOC gains, which simulations showed that the replacement of pastures stock change is the soil C stock in areas under green manage- ment practices in Brazil. The reference for the rates of C stock change is the soil C stock in areas under green manage- ment by 2020 n = 3. estimated by Bordonal et al. (2012). In this sense, we suggest the adoption of management systems involving ‘less aggressive’ tillage operations, to decrease the SOC losses in SG areas under GM in Brazil. Nowadays, more than 60% of Brazilian pastures are in some degree of degradation (Andrade et al., 2014). The replacement of degraded lands (with low soil C stocks) with high productivity energy crops may result in a positive soil C balance and additional C-savings for biofuels (Gelfand et al., 2013; Gollany et al., 2015). Our simulations showed that the replacement of pastures with sugarcane is associated with SOC gains, which partially offset the C debt resulting from the conversion of natural vegetation to pastures. One of the potential consequences of such LUC is the migration of livestock to other regions, increasing deforestation (Lapola et al., 2010). This indirect LUC, although very controversial, is now seen to have far less impact than previously thought (Macedo et al., 2015). Currently, government actions to improve pasture conditions (ABC Brazil, 2012), along with livestock production intensification, can effectively make large amounts of land available for alternative uses in Brazil. In this sense, we estimated a SOC accretion of 144 Tg if the projected increments on ethanol production were based on expansion of sugarcane into pasture areas in the next years in Brazil (Table 3).

DayCent simulations showed SOC losses of $0.19 \pm 0.04 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ in SG areas in Brazil with straw removal (Fig. 4). The harvest of crop residues is associated with potential environmental impacts, highlighting SOC losses (Wilhelm et al., 2007; Wortmann et al., 2010), as crop residues are a key component for SOC accretion (Paustian et al., 2016). Modeled SOC losses associated with straw removal in sweet sorghum showed that these emissions could eliminate all GHG mitigation benefits of bioethanol compared with gasoline (Wortmann et al., 2010). Using DayCent simulations, Miner et al. (2013) concluded that all stover is needed to be left in the field to maintain SOC levels in wheat, corn and grain sorghum areas in USA. Moreover, studies from Americas (Gollany et al., 2015), USA (Wilhelm et al., 2007), and Australia (Zhao et al., 2015) suggested that the SOC losses are the main constraint regarding the straw removal in agricultural areas for biofuels production. In this sense, the straw removal in SG areas in Brazil might be beneficial from an energy security point of view as more ethanol (or electricity)

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**Table 3** Sugarcane-cultivated area and soil C changes associated with the projected increase in ethanol production to meet the domestic demand in Brazil by 2030 in different scenarios

| Estimative                                      | Value              |
|------------------------------------------------|--------------------|
| Energy consumption in Brazil by 2030*          | 3529 TWh           |
| Sugarcane contribution to the energy supply by 2030† | 16%                |
| Ethanol contribution in the energy supply by sugarcane‡ | 88%                |
| Ethanol yield by 2030§                          | 10 000 L ha$^{-1}$ yr$^{-1}$ |
| Ethanol yield by 2030 including 2G technology¶ | 15 000 L ha$^{-1}$ yr$^{-1}$ |
| Expected Brazilian ethanol production by 2030** | 84.3 billions of L  |
| Expected sugarcane-cultivated area by 2030††   | 8.4 Million ha     |
| Expected sugarcane-cultivated area by 2030 (with 2G)†† | 5.6 Million ha    |
| Soil C changes in sugarcane areas between 2020 and 2050 with the increase in ethanol production based on LUC to pastures | 144 Tg C           |
| Soil C changes in sugarcane areas between 2020 and 2050 with the increase in ethanol production based on 2G ethanol (straw removal) | $-50$ Tg C         |

*Bronzatti & Iarozinski Neto (2008).
†NDC Brazil (2015).
‡12% to bioelectricity from sugarcane bagasse burning (Kutas, 2016).
§Based on the increments on ethanol yield in the last years (Goldemberg & Guardabassi, 2010).
¶Assuming that 2G technologies will increase the sugarcane ethanol yield about 50% (Kutas, 2016).
**Based on the sugarcane ethanol contribution in the energy supply by 2030 (NDC Brazil, 2015).
††Only for ethanol production. Currently, 59.4% of the sugarcane-cultivated area is harvested to ethanol production, while the remaining (40.6%) is used by sugar industry (UNICA, 2015).
will be produced, but not necessarily will result in the higher C-savings because the potential SOC losses associated (Fig. 4).

In Brazil, the development of technologies for 2G ethanol production has been moving at a slower pace than other places for many reasons but, now, seem to be accelerating. Currently, Brazil has two commercial 2G ethanol mills in operation, three demo mills, and 20 projects in the pipeline (Kutas, 2016). Moreover, substantial investment by the private sector and government is a strong market signal that sugarcane 2G ethanol supplies are likely to increase dramatically in the next years. In addition, straw removal in SG areas is also happening to support electricity production (Walter & Ensinas, 2010), such as currently in Lat_23S site. Therefore, straw removal is likely to become a common practice in Brazilian sugarcane areas soon and management practices must be proposed in order to mitigate the negative effects of the straw removal on SOC.

The adoption of no-tillage in SG areas with straw removal can decrease the rates of SOC losses comparing with areas under straw removal only (Fig. 4). In Brazil, SOC gains have been reported in sugarcane areas under no-tillage (Segnini et al., 2013). Century simulations showed that the adoption of no-tillage reduces the losses or even result in SOC gains in corn areas with stover harvest to ethanol production in USA (Sheehan et al., 2003). However, in our study, DayCent simulations showed positive SOC changes only when another source of C (vinasse and filter cake) was added (Fig. 4). According to Century simulations, vinasse and filter cake application were predicted to increase SOC in sugarcane areas in Brazil (Brandani et al., 2015). Filter cake and vinasse are produced in large quantities by the sugar-alcohol agro-industry. Moreover, the vertical integration of the sugarcane industry in Brazil makes the distribution of these subproducts easier because of shorter distances from the refinery to the field. In this sense, filter cake and vinasse applied to the soil is a practice widely used in SG areas in Brazil (Prado et al., 2013) and, as we observed, can have a prominent role on SOC dynamics in SG areas with straw removal. Despite its benefits, the adoption of no-tillage is not common in SG areas in Brazil. However, in a scenario with straw removal and possible SOC losses, we need to consider no-tillage during sugarcane crop renovation, mainly if it is combined with other best management practices, such as vinasse and filter cake application (Fig. 4). Lastly, we must mention that soil C accretion is finite and, under the same management practices and C inputs, the soil C stocks in these areas are expected to reach a new equilibrium over the next decades.

Without the contribution of 2G ethanol, we projected that the sugarcane area in Brazil is expected to expand by 3.04 Mha by 2030. With the full implementation of 2G ethanol production in the next years, we projected an expansion on SG area of only 0.23 Mha to meet domestic ethanol demands by 2030 (Table 3). LUC projections based on feedstock demands are a quite complex task and inherently uncertain. Moreover, the possible inclusion of 2G ethanol in the Brazilian energy supply in the next years increases the uncertainty about the land required for sugarcane production. Similarly uncertain are the spatial extrapolations about SOC, as C dynamics are known to be highly dependent on environmental characteristics and local management factors. In this sense, despite the limitations discussed above, the data presented in the Table 3 aim to show the likely direction and relative magnitudes of land conversions and SOC changes related in two feasible scenarios of SG expansion in Brazil. Moreover, our projections raised concerns about the sustainability of straw removal in SG areas. The SOC changes could be greater or less than estimated here, but our research can be a starting point for development of management strategies to mitigate possible SOC losses regarding 2G ethanol production in Brazil.

Based on land availability and positive effects on C-savings of sugarcane ethanol, we believe that stakeholders involved with the governance of bioethanol expansion should consider ways to incentivize sugarcane expansion on degraded pastures in Brazil. Moreover, we are sure that 2G technology will increase notably the energy output from sugarcane, but inferences about the net mitigation potential of 2G ethanol from sugarcane will require analysis of the entire biofuel life cycle, in which possible SOC losses should be taken into account. In this sense, field studies about the environmental suitability of straw removal in sugarcane areas are mandatory before using crop residues as a source of biomass for large-scale ethanol production in Brazil. Finally, the time horizon is quite relevant when evaluating soil C dynamics in agricultural areas (e.g., time since adoption of the GM system has great impact on the potential increase in SOC in sugarcane areas). However, extensive field measurements and data collection is costly or impossible, and thus, simulation models can help researchers to expand short-term field research to longer scenarios where field measurements are difficult to conduct. Our results supported that DayCent model can complement and extend the applicability of information collected in field studies (Campbell & Paustian, 2015; Robertson et al., 2015) and may be applied to obtain credible long-term assessments of sugarcane production effects on SOC in tropical regions.
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