GLOBAL CHANGE BIOLOGY
BIOENERGY

GCB Bioenergy (2017) **9**, 1333–1343, doi: 10.1111/gcbb.12411

Contribution of above- and belowground bioenergy crop residues to soil carbon

JOAO L. N. CARVALHO[1], TARA W. HUDIBURG[2], HENRIQUE C. J. FRANCO[1] and EVAN H. DELUCIA[3,4]

[1]*Laboratório Nacional de Ciência e Tecnologia do Bioetanol (CTBE), Centro Nacional de Pesquisa em Energia e Materiais (CNPEM), Rua Giuseppe Máximo Scolfaro 10000, Polo II de Alta Tecnologia, Campinas, SP, CEP 13083-970, Brazil,* [2]*Department of Forest, Rangeland and Fire Sciences, University of Idaho, Moscow, ID 83843, USA,* [3]*Department of Plant Biology, University of Illinois Urbana-Champaign, Urbana, IL 61801, USA,* [4]*Institute for Sustainability, Energy, and Environment, University of Illinois Urbana-Champaign, Urbana, IL 61801, USA*

Abstract

GHG mitigation by bioenergy crops depends on crop type, management practices, and the input of residue carbon (C) to the soil. Perennial grasses may increase soil C compared to annual crops because of more extensive root systems, but it is less clear how much soil C is derived from above- vs. belowground inputs. The objective of this study was to synthesize the existing knowledge regarding soil C inputs from above- and belowground crop residues in regions cultivated with sugarcane, corn, and miscanthus, and to predict the impact of residue removal and tillage on soil C stocks. The literature review showed that aboveground inputs to soil C (to 1-m depth) ranged from 70% to 81% for sugarcane and corn vs. 40% for miscanthus. Modeled aboveground C inputs (to 30 cm depth) ranged from 54% to 82% for sugarcane, but were 67% for miscanthus. Because 50% of observed miscanthus belowground biomass is below 30 cm depth, it may be necessary to increase the depth of modeled soil C dynamics to reconcile modeled belowground C inputs with measured. Modeled removal of aboveground corn residue (25–100%) resulted in C stock reduction in areas of corn–corn–soybean rotation under conventional tillage, while no-till management lessoned this impact. In sugarcane, soil C stocks were reduced when total aboveground residue was removed at one site, while partial removal of sugarcane residue did not reduce soil C stocks in either area. This study suggests that aboveground crop residues were the main C-residue source to the soil in the current bioethanol sector (corn and sugarcane) and the indiscriminate removal of crop residues to produce cellulosic biofuels can reduce soil C stocks and reduce the environmental benefits of bioenergy. Moreover, a switch to feedstocks such as miscanthus with more allocation to belowground C could increase soil C stocks at a much faster rate.

Keywords: bioenergy, corn, miscanthus, root biomass, sugarcane

Received 3 June 2016; accepted 8 November 2016

Introduction

Biofuels from bioenergy crops have been proposed as a strategy to mitigate GHG emissions, because CO_2 emitted by combustion of biofuels can be partially offset by uptake through photosynthesis. Ethanol is one of the most widespread biofuels at a global production of 93 billion liters in 2014, with the United States and Brazil producing 58% and 26% of this amount, respectively (Renewable Fuels Association, 2015). In the next decade, both countries will likely increase their domestic ethanol production and are expected to include second-generation ethanol produced from cellulosic feedstocks (Panoutsou *et al*., 2013; Goldemberg *et al*., 2014).

Correspondence: Evan H. Delucia, tel. 217 333 6177, fax 217 244 7246, e-mail: delucia@illinois.edu

Cellulosic ethanol can be produced from dedicated nonfood crops (e.g., miscanthus, switchgrass) and from crop residues. These two sources of raw material present both positive and negative impacts on GHG mitigation. For example, the production of cellulosic ethanol from perennial grasses has been associated with high yields, improved ecosystem health (Heaton *et al*., 2008), and reductions in GHGs (Davis *et al*., 2012; DeLucia, 2015). However, some land conversion may be required (Hudiburg *et al*., 2016), and the technology required for both agricultural and industrial stages of production is not yet well established (Ziolkowska, 2014; Santos *et al*., 2016).

Crop residues, mainly in the form of corn stover and sugarcane straw, are abundant in the United States and Brazil and currently are maintained on the soil surface or tilled into the soil. While the removal of these crop residues can be used to increase ethanol production on the same amount of land, the removals have the potential to adversely affect soil quality (Liska *et al.*, 2014). Returning crop residue improves soil quality by reducing risk of soil erosion and enhancing crop yield (Lal, 2005). Indiscriminate removal of crop residue can degrade soil quality by depleting soil carbon (C) (Campbell *et al.*, 2014; Liska *et al.*, 2014), with long-lasting adverse impacts on the environment (Lal, 2005). Thus, quantifying how much crop residue is required to maintain zero loss or to increase soil C stocks in the bioenergy sector is an important issue. This requires quantifying the relative contribution of above- and belowground crop residues to soil C. Anderson-Teixeira *et al.* (2013) evaluated corn production in Illinois and observed that 85% of C input into the soil was derived by aboveground residues and only 15% was associated with the root system. Similarly, Carvalho *et al.* (2013) observed that in Brazil aboveground sugarcane residue is the main source of C to the soil. In contrast to corn and sugarcane, miscanthus (*Miscanthus x giganteus*) allocates substantially more C belowground than aboveground (Anderson-Teixeira *et al.*, 2013). Regardless of the percentage of belowground contributions to soil C, it may not be necessary to maintain all aboveground crop residues on the soil surface to maintain or increase soil C compared to current practices, providing more raw material for cellulosic ethanol or bioelectricity.

Several studies have indicated that the amount of crop residue that can be removed from the field for bioenergy production will be site specific, varying according to edaphic and climatic conditions, crop type, and tillage practices. In the United States, Johnson *et al.* (2006) estimated that the average amount of corn residue biomass needed to maintain soil C stocks under moldboard plow tillage was 3.0 Mg C ha^{-1} yr^{-1} and with no-tillage management was 2.1 Mg C ha^{-1} yr^{-1}. Conventional tillage requirements are higher because tilling soil increases soil organic matter decomposition and reduces soil C stocks, mainly due to the disruption of soil aggregates and exposure of protected organic matter to microbial activity (Six *et al.*, 2002). Because the ratio of above- to belowground C inputs will vary by location and edaphic and climatic conditions, it is important to be able to quantify the changing ratio and residue removal rate for each management practice with process-based modeling.

Our primary goal was to facilitate the process of crop selection and management to maximize soil C sequestration in biofuel agroecosystems. To understand the relative contributions of above- and belowground plant parts to soil C as well as the impacts of crop residue removal on soil C stocks, this study was divided into three complementary objectives. The first objective was to review the literature to determine the range in above- and belowground C inputs to soil in areas cultivated with corn, sugarcane, and miscanthus. The second objective was to simulate the contribution of above- and belowground crop residues to soil C stocks at experimental sites under corn and miscanthus in the United States and under sugarcane in Brazil using the DayCent biogeochemical model (Parton *et al.*, 1998). The third objective was to model the impact of crop residue removal (for corn and sugarcane only) and tillage on soil C stocks over the next 30 years.

Materials and methods

Literature review

We performed a literature review of studies reporting soil C inputs in areas under sugarcane production in Brazil and under corn and miscanthus production around the world. The key words bioenergy crops, perennial grass, crop residues, corn residue, sugarcane residue, sugarcane trash, root system, root biomass, soil carbon inputs, carbon allocation, carbon retention rates, soil carbon stocks, and their associations were used as search terms in the ISI Web of Science database and in Google Scholar, yielding 158 papers overall. However, only 30 studies contained enough information to be included in our subsequent analyses (Table S1). We included papers that presented information about biomass production from above- and belowground crop residues or their biomass C contents. In some studies, we only found data for above- or belowground biomass production from bioenergy crops. When the C content of the crop residues was not included in the respective paper, we used a generic value of C content for sugarcane (344 and 440 g kg^{-1}, from below- and aboveground residues, respectively; Fortes *et al.*, 2013), for corn (375 and 421 g kg^{-1} from below- and aboveground residues, respectively), and for miscanthus (371 and 429 g kg^{-1}, from below- and aboveground residues, respectively; Anderson-Teixeira *et al.*, 2013). It is important to highlight that the observed estimates of belowground C inputs from bioenergy crops did not include C input from rhizodeposition. Values reported in the literature for belowground biomass and production ranged from 1-m depth totals to increments of 10 to 30 cm up to 1 m in depth. For this reason, we used the 1-m depth total as we could not consistently match the increment depths across studies.

Study sites for model simulations

Sugarcane. Model simulations were conducted for two locations in São Paulo, Brazil, that differed in soil texture. Soils at Pradópolis (21°15′S, 48°18′W) are classified as Rhodic Eutrudox, while soils at Jaboticabal (21°20′S, 48°19′W) are classified as Typic Kandiudox (Table 1). Tillage practices, fertilizer applications, and weed control for Jaboticabal and Pradópolis are reported in Franco *et al.* (2010, 2011) and in Fortes *et al.* (2011, 2012), respectively. At both sites, the regional climate was classified as Tropical Savanna, characterized by a rainy summer and dry winter, with average annual precipitation of 1560 mm and average annual temperature of 22.9°C. Experiments established at these locations were implemented to evaluate the effect of nitrogen fertilization under nonburning management on sugarcane yield and nitrogen cycling. In both experiments, the production of aboveground (stalks, tops, and dry leaves) and belowground biomass (roots and rhizomes) was evaluated during four years (plant cane and three ratoons). A ratoon is a method of harvesting a sugarcane crop which leaves the roots and the lower parts of the plant uncut to decrease cost of planting and preparing fields the following years. In Brazil, an unharvested plant cane year followed by three or four ratoon harvests is a typical management practice.

Corn and miscanthus. The University of Illinois Energy Farm is located in central Illinois (40.06°N, 88.19°W; Table 1). Miscanthus (*Miscanthus* × *giganteus*) and a corn–corn–soybean annual rotation have been grown side-by-side at the Energy Farm since 2008. The corn–corn–soybean rotation is typical for central Illinois, although the study site supported a mixture of alfalfa and the traditional corn–soybean rotation over the last century. Annual precipitation has averaged 1040 mm yr^{-1} over the last 30 years. The soil is a deep and fertile silt loam Flanagan typical of the region with some low-lying sections of Drummer (Smith *et al.*, 2013). Measurements at the Energy Farm include above- and belowground live and dead biomass, biomass C and nitrogen content, annual harvested C and nitrogen removals, annual soil C content including C isotope signatures, soil texture, nitrous oxide (N_2O) emissions, nitrate leaching (NO_3), and eddy covariance for net CO_2 exchange between the vegetation and the atmosphere (Anderson-Teixeira *et al.*, 2013; Smith *et al.*, 2013; Zeri *et al.*, 2013).

Model description and simulations

Model simulations of crop yield, residue removals, and soil C dynamics were performed using the DayCent biogeochemical model (v. 4.5; Del Grosso *et al.*, 2011), the most recent daily time step version of CENTURY. We focused on the major first-generation bioenergy crops in Brazil and the USA, sugarcane and corn, and a potential second-generation crop, miscanthus. DayCent simulates the effects of climate and land-use change on C and nutrient cycling in terrestrial ecosystems and has been validated for use in crop and grassland ecosystems globally (Del Grosso *et al.*, 2009; Campbell *et al.*, 2014; Cheng *et al.*, 2014; Hudiburg *et al.*, 2015), including recent modifications to simulate sugarcane production (Duval *et al.*, 2013). Required inputs for the model include vegetation cover, daily precipitation and temperature, soil texture, and current and historical land-use practices. DayCent calculates the potential plant growth as a function of water, light, and soil temperature, and limits actual plant growth based on soil nutrient availability. Soil organic C is estimated from the turnover of soil organic matter pools, which change with the decomposition rate of crop residues. The model includes three soil organic matter pools (active, slow, and passive) with different decomposition rates, above and belowground litter (residue) pools, and a surface microbial pool associated with the decomposing surface

Table 1 Characterization of the study sites used for the DayCent simulations. Soil data refer to a soil depth of 0–30 cm

Crop	Sugarcane		Corn–corn–soy	*Miscanthus*
Location	Jaboticabal, SP, Brazil 21°20′S; 48°19′W	Pradópolis, SP, Brazil 21°15′S; 48°18′W	Urbana, IL, USA 40°3′N; 88°11′W	Urbana, IL, USA 40°3′N; 88°11′W
Elevation (m)	600	580	233	233
Soil classification	Typic Kandiudox (Soil Survey Staff, 2010)	Rhodic Eutrudox (Soil Survey Staff, 2010)	Flanagan silt loam	Flanagan silt loam
Sand (g kg^{-1})	658	135	160	160
Silt (g kg^{-1})	54	227	580	580
Clay (g kg^{-1})	288	638	260	260
Bulk density (g cm^{-3})	1.31	1.30	1.36	1.36
C content (%)	1.33	1.80	1.61	1.61
pH	6.3	5.3	6.3	6.3
Rainfall (mm)	1382	1580	1040	1040
Aboveground biomass (Mg C ha^{-1}, includes harvestable biomass and residue)				
First year or plant cane*	24.8	27.3	10.1	1.0
Second year or first ratoon	18.3	14.9	9.3	3.5
Third year or second ratoon	19.3	9.3	3.0 (soy)	11.6
Fourth year or third ratoon	19.4	20.6	7.8	14.3
Belowground biomass (Mg C ha^{-1}, include roots and rhizomes)				
First year or plant cane	2.4	3.0	0.2	0.3
Second year or first ratoon	2.2	1.8	0.6	1.5
Third year or second ratoon	1.5	0.9	0.5	4.2
Fourth year or third ratoon	1.0	1.1	na	na

*First year (plant cane) is allowed to grow for 18 months before harvest, while subsequent years (ratoons) only grow for 12 months prior to harvest resulting. This results in a higher yield from the first harvest.

litter. Above- and belowground plant residues are partitioned into structural and metabolic pools as a function of the lignin-to-N ratio in the residue. With increases in the ratio, more of the residue is partitioned to the structural pools, which have slower decay rates than the metabolic pools. Transfers between pools (above- and belowground structural pools to soil pools) are balanced in DayCent on a daily basis and can be summarized in yearly output files. For example, structural surface litter C is transferred to fast or intermediate surface organic matter C and then, in the absence of tillage or soil disturbance, this litter (residue)-derived C can be tracked as it enters soil C pools from the intermediate surface organic matter pool (cannot enter from the fast surface organic pool). For this study, we define this transfer between the surface structural pool and the intermediate soil pool (some of which can be transferred to the fast and slow soil C pools) as our aboveground inputs. Belowground inputs include C flow from the dead mature and fine root pools to fast and intermediate soil C pools and the soil metabolic pool to the fast soil C pool. Carbon in the fast soil C pool that is not respired can flow to the intermediate and slow pool, and intermediate soil C that is not respired can flow to the slow C pool. For this study, we define annual belowground inputs as the sum of the C flow between the dead and mature fine root pools to the soil fast and intermediate pools, plus the soil C flow from the soil metabolic pool to the soil fast C pool. Changes in soil C accumulation are determined by tracking the change in total soil C each year (can be positive or negative), where positive increases indicate higher contributions of recalcitrant residues to the intermediate and slow C pools. Net change in soil C is simply the total sum of each annual change.

DayCent was parameterized to model soil organic C dynamics to a depth of 30 cm (maximum depth available in DayCent). While total belowground biomass and production is estimated for the full rooting zone (2 m), belowground inputs from roots and rhizomes are only included for the top 30 cm of soil C cycling. Crop parameters were directly calibrated using site data (Table S2). Daily climate data were used for the corresponding data years at each site, and a longer climate record (1980–2011) was used for historical and future simulations. This longer climate record for the US site was downloaded from the Daymet database (http://www.daymet.org; Thornton *et al.*, 2012) and from WorldClim (www.worldclim.org; Hijimans *et al.*, 2005) for the sugarcane sites in Brazil.

Historical simulations at the Energy Farm followed a standard native prairie with a short fire return interval schedule followed by ~150 years of agricultural history. Agricultural history included corn–soy rotations, alfalfa, and wheat. Soil C stocks were simulated to represent the preagricultural native prairie levels with a subsequent decline, as the land was cultivated each year for the annual crops. Following the agricultural history, the Energy Farm simulations were run from 2008 to 2012 duplicating the site management and future scenario simulations (2012–2041) were run using a 15-year rotation for miscanthus. For corn and sugarcane, we simulated 0%, 25%, 50%, 75%, and 100% residue removal management to determine whether there was a residue removal rate at which there was no C loss penalty compared with no residue removal. For miscanthus, we did not simulate crop residue removal because 90% of biomass (stem and leaves) is collected during harvest operations.

Historical simulations for sugarcane followed a typical Atlantic Forest deforestation and then ~30 years of sugarcane cultivation. Similarly, soil C stocks were simulated to represent the preagricultural Atlantic Forest levels with a subsequent decline as the land was cultivated with burned sugarcane until 1998 and 2004 in Pradópolis and Jaboticabal, respectively. After this time, the areas were cultivated (conventional and conservation tillage) sugarcane without burning. Sugarcane simulations were run for the experimental period (2005–2009), and future simulations (2009–2038) were run using a sugarcane cycle of six years. The sugarcane crop cycle typically lasts five to six years, which includes the first year plant cane cycle (18 months) and the ratoons (harvestable biomass) that grow subsequently. Ratoons are harvested annually until sugarcane yield becomes uneconomical and a new planting is required. We simulated the standard application rates of 40 kg and 100 kg ha^{-1} N, respectively, for the plant cane and ratoon cycles.

Recently, the DayCent model was calibrated and improved to estimate the variation in soil C stocks in areas under corn and miscanthus at the Energy Farm in Illinois (Hudiburg *et al.*, 2015) and sugarcane in Florida (Duval *et al.*, 2013). Hudiburg *et al.* (2015) showed 60–95% agreement for biomass yield and soil C stocks for both crops across a range of site conditions in the Eastern United States. For the Energy Farm, model-data correlations for multiple monthly biomass observations (above- and belowground) were an r^2 of 0.94 for miscanthus and 0.92 for corn–corn–soy (Fig. S1). We used a synthesis of observed data (NPP, biomass yield, soil C) to validate the model for the sugarcane simulations in Brazil. Observations were from Carvalho *et al.* (2013), Franco *et al.* (2010, 2011), Fortes *et al.* (2011, 2012, 2013), and Otto *et al.* (2009). Model-data correlation for multiple observations of sugarcane annual total biomass was an r^2 of 0.65 (Fig. S1).

Results

Literature review of the input of C from above- and belowground crop residues

Averaged across all studies, aboveground C inputs were considerably larger than belowground inputs (up to 1 m depth) for sugarcane and corn, while the opposite was observed for miscanthus (Fig. 1). The average C input from sugarcane root system (roots plus rhizomes) was 1.88 Mg ha^{-1} yr^{-1} (ranging from 0.83 to 3.7 Mg ha^{-1} yr^{-1}), while the amount of C from aboveground residue was 5.44 Mg ha^{-1} yr^{-1} (ranging from 3.33 to 7.57 Mg ha^{-1} yr^{-1}) (Table S3). Rhizomes presented higher biomass (68%) than roots (32%). In clay soils, a reduction in belowground C inputs with the increased sugarcane age was observed (Carvalho *et al.*, 2013), while in sandy soil, the inverse behavior was reported (Silva-Olaya, 2014).

Corn roots represented only 19% of total C input ranging from 0.39 to 1.63 Mg ha^{-1} yr^{-1}, while corn aboveground residue input represented 81% of the total (Fig. 1 and Table S4). For areas under miscanthus cultivation, the amount of C allocated to belowground pools (roots plus rhizomes) was 2.4 times higher compared to those observed in aboveground residues (Fig. 1 and Table S5). In miscanthus areas, the average belowground C input (roots and rhizomes) was 5.78 Mg ha^{-1} yr^{-1} and aboveground residues comprised an average C input of 2.37 Mg ha^{-1} yr^{-1}.

Model simulation of the contribution of above- and belowground residues to soil C stocks

Model simulations indicated that aboveground sugarcane residue was the main source of C to the soil and represented 54% and 82% of the total C input for Jaboticabal and Pradópolis, respectively (Fig. 2). At both sites, the largest contribution of the root system to soil C occurred during the replanting time (Fig. 2 – blue bars). The 30-year simulation indicated that maintenance of sugarcane residue on the soil surface would result in increases in soil C stocks of 5.7 and 2.8 Mg C ha^{-1} in Jaboticabal and Pradópolis, respectively.

At the Urbana, IL miscanthus site, the 30-year model simulation indicated a net increase in soil C stocks of 56 Mg ha^{-1} with belowground contributions from roots and rhizomes responsible for 33% of total C inputs (Fig. 3a). The largest contributions to changes in soil C were from aboveground miscanthus residues during the crop cycle (orange bars), while significant belowground contributions occurred during the replanting year after the soil was tilled (blue bars).

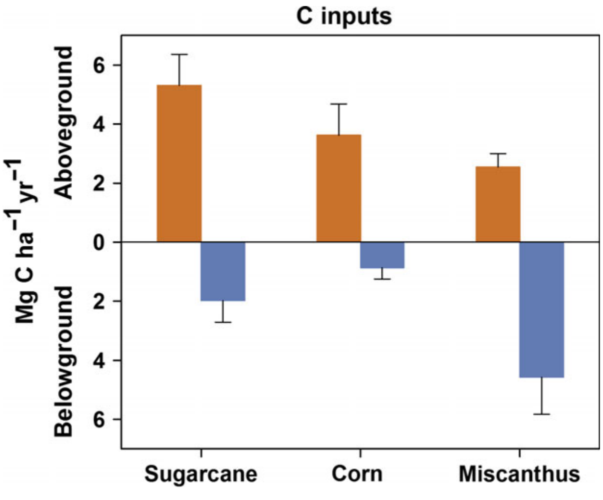

Fig. 1 Input of C from below- and aboveground crop residues in areas under sugarcane, corn, and miscanthus cultivation. Data represent the average (± standard deviation) of the results included in literature review. The figure represents the relative contributions *without* residue removal.

Corn–corn–soy simulations in Illinois indicated a long-term reduction in soil C stocks. It was not possible to separate the modeled annual contribution of above- and belowground crop residues in corn fields, because corn is simulated with cultivation events in the spring that incorporates aboveground residues into the soil mixing the two pools. In general, we observed a net C sequestration in corn years and net C emission in soybean years (Fig. 3b).

Modeled effects of corn residue and sugarcane residue removal on soil C stocks

Conventional corn tillage without residue removal reduced soil C stock by 1.6 Mg ha^{-1} over 30 years (Fig. 3b). If corn residue was removed for ethanol production, reductions of 4.0, 6.4, 8.9, and 11.5 Mg C ha^{-1} would be expected for scenarios of 25%, 50%, 75%, and 100% of corn residue removal, respectively. In contrast, no-till management and up to 75% removal of corn residue increased soil C stocks from 2.3 to 10.1 Mg C ha^{-1} (Fig. 4). In both areas under sugarcane (Fig. 4), no residue removal for a 30-year period promoted an increase in soil C stocks of 5.7 and 2.8 Mg ha^{-1} for Jaboticabal and Pradópolis, respectively. The model predicted reductions in soil C stocks only with 100% of sugarcane residue that was removed at the Pradópolis site.

Discussion

Contribution of C from above- and belowground crop residues

The literature review and modeling results indicated that aboveground sugarcane residues, composed of tops and dry leaves, were the main input of C to the soil, which on average represented more than three times the potential C input from the root system. This is partially because after a harvest large amounts of residue, ranging from 10 to 20 Mg ha^{-1} yr^{-1} (dry basis), are left on the field (Robertson & Thorburn, 2007; Fortes *et al.*, 2012; Carvalho *et al.*, 2013), and heavy machinery traffic reduces root system development and its contribution to soil C. Moreover, studies that reported multiple years (plant cane and ratoons) of both above- and belowground data showed that a reduction in belowground C inputs was observed with an increase in age of sugarcane fields in clay and sand clay loam soils (Carvalho *et al.*, 2013), while in sandy soil, the opposite behavior was observed (Silva-Olaya, 2014). In sandy soils, the resistance to root penetration is less intense and these

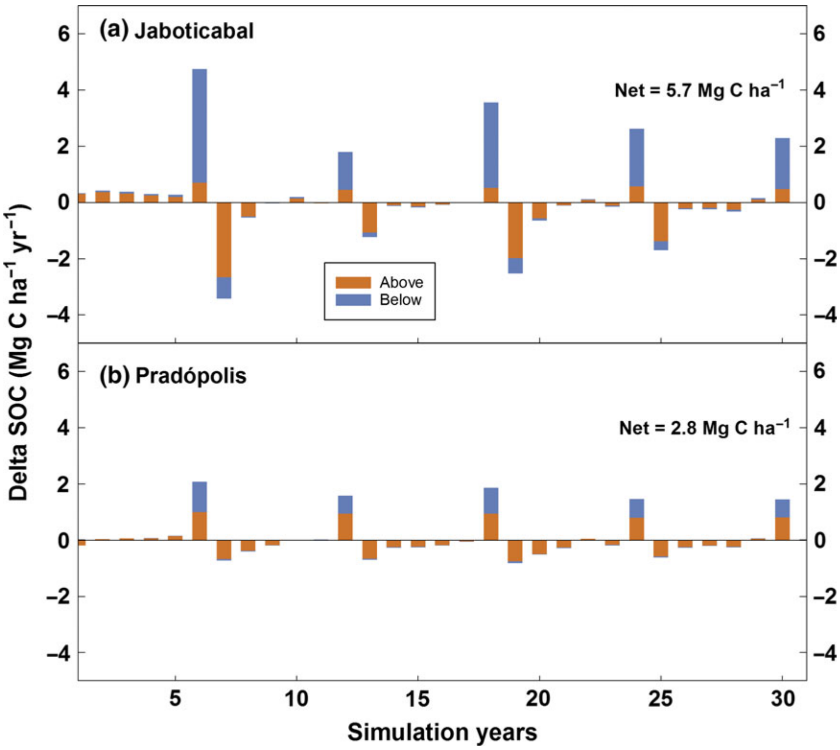

Fig. 2 Estimated contribution of above- and belowground sugarcane residues to soil C stocks by the DayCent model. Model simulations maintained all sugarcane residues on the soil surface in Jaboticabal (a) and Pradópolis (b). Positive values indicate soil C accumulation (less C respired), and negative values indicate soil C losses in the respective agricultural year (more C respired). 'Net' indicates the summed change in SOC over the entire simulation period. The large increases in delta soil C (e.g., year 6 for sugarcane) are associated with incorporation of roots and rhizomes as structural soil C although tillage practices to plant a new crop and the subsequent decreases represent the decomposition of the labile C from tilled above- and belowground inputs.

soils hold less water, making a deeper root system necessary to ensure adequate water supply.

Our model simulations indicated that soil clay content reduced the root contributions to soil C. At Jaboticabal (soil with 29% clay), a 30-year simulation indicated a net increase in soil C stocks of 5.7 Mg ha^{-1} with root systems responsible for 46% of the total inputs. In the very clayey soil at Pradópolis, the root system had a lower total contribution to soil C stocks (18%) and most of this input occurred during the soil preparation at replanting (every 6 years), resulting from mortality and incorporation of roots and rhizomes. Because of this, it is likely that contributions to the top 30 cm of soil C will remain dominated by aboveground inputs over time; however, the ratio could change as the more slowly decomposed rhizomes are incorporated into soil organic matter at each replanting event.

Corn typically has a high shoot/root ratio, and we found that the average ratio of shoot residue to root residue was 4.2. Anderson-Teixeira *et al.* (2013) observed that the C inputs from corn came predominately from aboveground litter inputs, which occur in the fall, shortly before or at the time of harvest (eventually, these were mixed into the surface soil layer through tillage), and from roots, which are minimal below the top 30 cm of soil. Corroborating this observation, Osaki *et al.* (1995) found that ~80% of total root biomass in corn is concentrated in the top 20 cm that can be exposed and mixed with conventional tillage practices.

It is important to highlight that our literature review data, as well as those data reported by Anderson-Teixeira *et al.* (2013), did not include the belowground C inputs resulting from root exudates and root turnover during the growing season. Several studies have indicated that a significant proportion of C input in corn fields came from rhizodeposition (Bolinder *et al.*, 1999; Amos & Walters, 2006; Kumar *et al.*, 2006). Amos & Walters, 2006 concluded that C rhizodeposition from corn roots is equivalent to 29% of aboveground biomass C. Despite belowground residue contributing to a lower potential biomass C input, this pool plays a critical role in building and maintaining SOC (Johnson *et al.*, 2014), especially due to rhizodeposition inputs and the higher potential C retention rates. According to Bolinder *et al.* (1999), the rate of biomass C

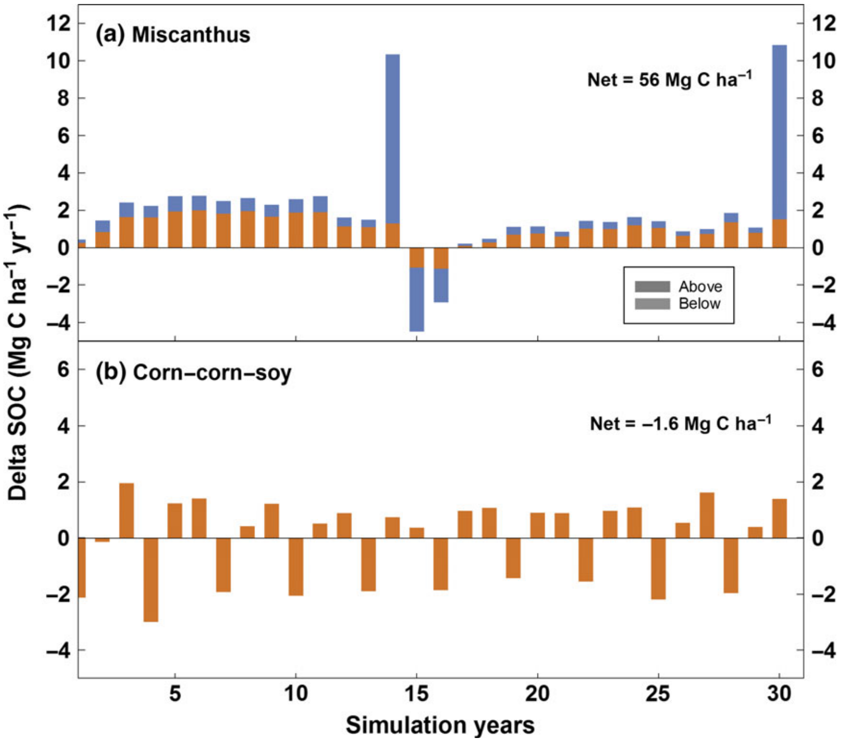

Fig. 3 Estimated contribution of above- and belowground miscanthus residues in Illinois (a) and annual contribution of crop residues in the area under rotation of corn, corn, and soybean under conventional tillage in Illinois (b). 'Net' indicates the net change in SOC over the entire simulation period. Positive values indicate soil C accumulation, and negative values indicate soil C losses in the respective agricultural year. 'Net' indicates the summed change in SOC over the entire simulation period. The large increases in delta soil C (e.g., year 14 for miscanthus) are associated with incorporation of roots and rhizomes as structural soil C although tillage practices to plant a new crop and the subsequent decreases represent the decomposition of the labile C from tilled above- and belowground inputs.

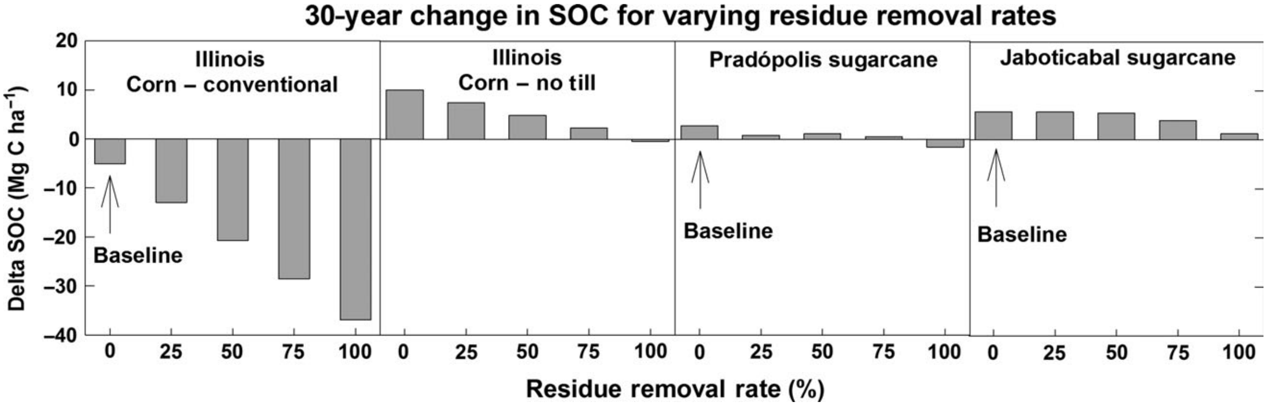

Fig. 4 Modeled soil C stocks influenced by crop residue removals and tillage practices. Residue removal was not simulated for miscanthus because standard harvest practices remove nearly 90% of the aboveground crop as a cellulosic ethanol feedstock.

transformed into soil organic matter as the result of root system decomposition is higher than aboveground biomass. These authors observed a higher C retention rate of belowground corn residues (21% – ranging from 14% to 30%) in comparison with aboveground residues (13%).

The higher C retention rate of the belowground residues can be explained by chemical composition, because roots have a higher concentration of phenolic and lignaceous compounds (Bolinder *et al.*, 1999) and because promoting soil aggregation enhances the physical protection of C added directly into the soil (Oades, 1995). In view of this, it has been estimated that roughly two-thirds of corn soil organic C is originated from belowground inputs (Bolinder *et al.*, 1999; Johnson *et al.*, 2006).

The 30-year simulation indicated that the corn–corn–soybean crop rotation under conventional tillage, typically used in Central Illinois, resulted in a small reduction in soil C stocks. Our results indicated soil C losses in soybean years and soil C gains during corn years, which is in agreement with previous field evaluations performed in the same study area (Zeri *et al.*, 2011; Anderson-Teixeira *et al.*, 2013).

Modeled results indicated that belowground inputs to soil C from miscanthus were 34% of total inputs over a 30-year simulation. Observations suggest that this input is as high as 60% when considering a rooting depth of 1 m. Soil C dynamics to a depth of 1 m are especially important to consider for perennial grasses such as miscanthus because a significant proportion of root biomass can occur at depths below 30 cm (Anderson-Teixeira *et al.*, 2013). With a modeled rotation cycle of 15 years, it was observed that miscanthus aboveground biomass, represented by natural litter fall and residues added after harvest, was the main source of C to the soil during the crop cycle in the top 30 cm and the majority of the C input from root system (mainly rhizomes) occurred only after soil tillage. Modeled soil C only includes senesced (dead) root C and litter inputs and does not include the living rhizomes and roots that do not die on an annual basis, making the literature review observations (based on total belowground biomass) difficult to compare with the modeled results for perennial grasses. Similar to the sugarcane simulations, greater inputs of C from the root system were observed after soil tillage during replanting when roots and rhizomes are crushed and mixed with soil particles, increasing the C addition to the soil and accelerating live root C turnover rates. Nevertheless, literature observations and model data are in agreement that total contributions to soil C are greater for miscanthus than for corn and sugarcane.

Senesced miscanthus litter has high lignin and low nutrient content resulting in low rates of litter decomposition and high potential for soil C accumulation (Arundale *et al.*, 2014). The model simulations indicated an increase in soil C stocks at a mean annual rate of 1.87 Mg ha^{-1}. The higher soil C accumulation for miscanthus can be explained in part by the absence of tillage during the 15 years of growth, because the corn–corn–soy baseline system is losing soil C as the fields are plowed each year (Bernacchi *et al.*, 2005). Our findings are supported by previous studies performed in central Illinois using eddy-covariance data that indicate the miscanthus plots are storing around 2.0 Mg C ha^{-1} yr^{-1} (Zeri *et al.*, 2013), as well as modeling estimates of C accumulation rates ranging from 0.5 to 2 Mg ha^{-1} yr^{-1} (Hudiburg *et al.*, 2015). However, Hudiburg *et al.* (2015) evaluated only the total accumulation rates, without discriminating the source of this C. Our simulations indicated that a higher percentage of total soil C inputs were derived from aboveground sources. While Anderson-Teixeira *et al.* (2013) showed that the largest contribution to soil C was from investment in belowground biomass, this included the belowground contributions in deeper soil layers, which were not considered in the model. In addition, Anderson-Teixeira *et al.* (2013) evaluated only the establishment period of the crop (around 3 years), while we simulated the long-term impact of miscanthus cultivation on soil C stocks which included higher litter inputs over time as litter accumulated in noncultivation years. Because of this, it is likely that contributions to the top 30 cm of soil C will remain dominated by aboveground inputs but when considering the complete rooting zone, total soil C inputs may be dominated by belowground inputs. Modifications would need to be made to DayCent or a different model would need to be used to test this hypothesis.

Impact of residue removal and tillage on soil C stocks

The removal of crop residues for industrial uses may negatively affect soil C stocks and agricultural productivity (Lal *et al.*, 2004; Wilhelm *et al.*, 2004; Blanco-Canqui & Lal, 2007; Smith *et al.*, 2012; Marin *et al.*, 2014). DayCent simulations indicated that the impacts of corn residue removal on soil C stocks were dependent on tillage operations and the rate of residue removed (Fig. 4). Currently, corn production at the University of Illinois Energy Farm is based on conventional tillage with no corn residue removal, which resulted in a small reduction in simulated soil C stocks. Our simulations indicated that it is just as important to maintain the corn residue in the field as it is to adopt no-tillage management. The residue removal rates in areas under conventional tillage reduced soil C stocks, proportionally. However, when no-till was simulated, the partial removal of crop residues did not result in reductions in C stocks compared to the baseline scenario.

In no-till management, less C input was necessary to maintain soil C stocks at the baseline level, because less C is lost by soil disturbance. Our modeling estimates were corroborated by Wilhelm *et al.* (2007) and Johnson *et al.* (2006) who observed that the adoption of no-tillage in place of conventional tillage reduces the need for corn residue to maintain soil C stocks and consequently increases the amount of corn residue that could be harvested in a sustainable way. In agreement, Graham *et al.* (2007) pointed out that the available amount of corn residue in Nebraska more than doubled when no-tillage is practiced.

In agreement with our model simulations, field measurements show that complete corn residue removal in the Corn Belt reduces soil C stocks (Clapp *et al.*, 2000; Liska *et al.*, 2014). Moreover, Blanco-Canqui & Lal (2007) observed reductions in C stocks when more than 25% of the corn residues were removed in areas under no-tillage management in Ohio, and our model simulations suggest that this trend continues for increased removal rates (Fig. 4). Liska *et al.* (2014) used a modeling approach and concluded that the total corn residue removal in the Corn Belt could decrease regional net soil C stocks by an average of 0.47–0.66 Mg C ha^{-1} yr^{-1}, and this additional emission when included with cellulosic ethanol life cycle assessment will probably exceed the US legislative mandate of 60% reduction in GHG emissions compared with gasoline. The DayCent simulations show close to 1 Mg of soil C lost per year with 75% to 100% removal rates under conventional tillage (Fig. 4); however with no-till management even at the 100% removal rate, soil C increased compared to baseline with conventional tillage.

The effects of sugarcane residue removal on soil C stocks were less severe than for corn. The main explanation of these results may be associated with sugarcane physiology and life cycle compared with corn, such as a well-developed root system, higher production of aboveground crop residues, and the lower frequency of tillage operations. In sugarcane fields, tillage operations are performed every five to six years, minimizing their impact on soil C stocks. Segnini *et al.* (2013) isolated the impacts of maintenance of the sugarcane residue on the soil surface and soil disturbance, and observed that most of accumulated C during the sugarcane cycle was lost after tillage operations in sugarcane replanting. According to these authors, the maintenance of the sugarcane residue under conventional tillage resulted in annual C accumulation rate of 0.69 Mg ha^{-1}, while the adoption of no-tillage with the same amount of the residue resulted in a C retention rate of 1.63 Mg ha^{-1} yr^{-1}.

The higher response of sugarcane residue removal on soil C stocks observed in Jaboticabal may be associated with lower initial soil C content and the lower clay content (Table 1). In Jaboticabal, the simulations indicated a long-term increase in C stocks independent of the residue removal rates. At Pradópolis, soil C was less responsive to residue removal mainly due to the higher clay content, higher initial C content, and lower C input from root system and aboveground residues along the sugarcane cycle (Table S2). The organo-mineral interactions between C and clay stabilize soil C, as does the spatial inaccessibility of labile C inside abundant microaggregates in clay soil (Dieckow *et al.*, 2009). However, it is important to highlight that the C stock results were obtained only by modeling without validation, and field experiments are needed to confirm whether this would occur in field conditions in Brazil.

In summary, our study indicates that aboveground crop residues are the main C-residue source to the soil in the current bioethanol sector (corn and sugarcane) and that indiscriminate removal of crop residues to produce cellulosic biofuels can reduce the soil C stocks and attenuate the GHG mitigation in comparison with fossil fuels. The magnitude of the C losses resulting from residue removal varies by crop type, tillage operations, weather conditions, and soil texture. The adoption of conservationist tillage practices could considerably increase the amount of collectable agricultural residues to industrial use without jeopardizing soil C stocks. This study also indicates that belowground inputs to soil C were significantly higher for miscanthus vs. corn and sugarcane and can exceed aboveground inputs when considering the entire rooting zone emphasizing the potential for miscanthus as a GHG reducing feedstock. While we synthesized the literature and modeled C inputs belowground as biomass, the turnover rates of belowground biomass and the relative contribution of rhizodeposition to stable belowground C pools are key uncertainties in evaluating the effect of different crop types and their management on soil C.

Acknowledgements

This research was supported by funding from São Paulo Research Foundation – FAPESP (Process Number 2013/13451-0), the Energy Bioscience Institute, NSF Idaho EPSCoR Program under Award Number IIA-1301792. We thank Professor Paulo Trivelin to supply sugarcane data from the FAPESP Project Number 2002/10534-8.

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Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

Table S1. References from the literature review describing soil C inputs under energy crops.
Table S2. Crop parameters that vary by crop type for the DayCent simulations.
Table S3. Input of C from below and aboveground crop residues in sugarcane fields in Brazil.
Table S4. Input of C from below and aboveground crop residues in areas under corn cultivation.
Table S5. Input of C from below and aboveground crop residues in areas under miscanthus cultivation.
Figure S1. Observed vs. modeled biomass for (A) Sugarcane in Brazil.
Figure S2. Change in soil C (in g C m^{-2} yr^{-1}) over time (simulation year) for each of the crops simulated.