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Input of sugarcane post-harvest residues into the soil

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ABSTRACT: Sugarcane (*Saccharum* spp.) crops provide carbon (C) for soil through straw and root system decomposition. Recently, however, sugarcane producers are considering straw to be removed for electricity or second generation ethanol production. To elucidate the role of straw and root system on the carbon supply into the soil, the biomass inputs from sugarcane straw (tops and dry leaves) and from root system (rhizomes and roots) were quantified, and its contribution to provide C to the soil was estimated. Three trials were carried out in the State of Sao Paulo, Brazil, from 2006 to 2009. All sites were cultivated with the variety SP81 3250 under the green sugarcane harvest. Yearly, post-harvest sugarcane residues (tops, dry leaves, roots and rhizomes) were sampled; weighted and dried for the dry mass (DM) production to be estimated. On average, DM root system production was 4.6 Mg ha^{-1} year^{-1} (1.5 Mg C ha^{-1} year^{-1}) and 11.5 Mg ha^{-1} year^{-1} (5.1 Mg C ha^{-1} year^{-1}) of straw. In plant cane, 35 % of the total sugarcane DM was allocated into the root system, declining to 20 % in the third ratoon. The estimate of potential allocation of sugarcane residues to soil organic C was 1.1 t ha^{-1} year^{-1}; out of which 33 % was from root system and 67 % from straw. The participation of root system should be higher if soil layer is evaluated, a deeper soil layer, if root exudates are accounted and if the period of higher production of roots is considered.

Introduction

In sugarcane (*Saccharum* spp.) fields, the main inputs to soil organic carbon (SOC) come from post-*harvest sugarcane residues, either aboveground* (dry leaves and tops, referred as straw) or belowground components (rhizomes and roots, referred as root system). In the 2000s, the effects of keeping sugarcane straw on soil surface were evaluated by several researchers under different approaches (Gava et al., 2001; Galdos et al., 2009; Robertson and Thorburn et al., 2007a; Thorburn et al., 2012; Fortes et al., 2012; Souza et al., 2012), but few authors approached the root system (Ball-Coellho et al., 1992; Otto et al., 2009; 2011; Azevedo et al., 2011), especially its potential for supplying C to the soil.

Keeping sugarcane straw on soil surface shows several positive effects to the soil, such as: more nutrient cycling (Oliveira et al., 1999), higher water-holding capacity (Dourado-Neto et al., 1999), higher aggregate stability (Graham et al., 2002), increase of the SOC stocks (Galdos et al., 2009), reduction of the greenhouse gas emissions (Galdos et al., 2010) and increase of sugarcane yield (Gava et al., 2001). However, despite the several benefits of maintaining sugarcane residues over the soil, sugarcane producers have considered to partly remove these residues for electricity and second generation ethanol production.

In Brazil, some initiatives have focused on estimating the amount of straw needed to be left on soil surface in order to maintain sustainability of sugarcane fields. However, most of the researchers do not take into account the quality and potential of plant compartments for supplying C and nutrients to the soil. Sugarcane straw is a heterogeneous material, composed of dry leaves and tops. Dry leaves are often more abundant and present lower moisture and lower nutrient concentration when compared to tops (Franco et al., 2010; Fortes et al., 2011). Root system comprises roots and rhizomes, and little is known about its chemical structure or its contribution to supply C to the soil. The root system represents a significant C input to the soil (Ball-Coelho et al., 1992). Nevertheless, although root biomass is an important component of soil C cycling, little is known about the real contribution of this plant compartment in supply C to the soil, neither in terms of root turnover nor of their lifespan in the soil (Smith et al., 2005).

It is essential to determine the actual contribution of aboveground and belowground residues in supplying organic matter to the soil in order to determine the sustainability of removing sugarcane straw for industrial purposes. Based on that, this study hypothesized that root system is the most important supplier of organic material to the soil, allowing partial removal of straw from sugarcane field without further negative effects on SOC stocks in the long term. This study aimed to quantify biomass inputs from sugarcane straw (tops and dry leaves) and from root system (rhizomes and roots), and estimating its contribution to provide C to the soil.

Materials and Methods

Description of experiments

Three field trials were set up in Southeast of Brazil, in the State of Sao Paulo, the largest sugarcane producer in Brazil. Details of experimental sites are shown on Table 1, and results of chemical and physical characterization of soil performed at the beginning of the experiment are shown on Table 2. Weather data were obtained from weather stations located less than 2,000 m away from

Table 1 – Details of experimental sites.

	Experimental sites		
	Site 1	Site 2	Site 3
Location	Pirassununga, SP 21°55' S; 47°11' W	Jaboticabal, SP 21°20' S; 48°19' W	Pradopolis, SP 21°15' S; 48°18' W
Altitude (m)	650	600	580
Reference	Franco et al. (2010, 2011)	Franco et al. (2010, 2011)	Fortes et al. (2012)
Variety	SP81 3250	SP81 3250	SP81 3250
Replicates	16	16	16
Plot size (m^2)	270	270	270
Space between rows (m)	1.50	1.50	1.50
Soil tillage	Herbicide application, chisel plowing (0.40 m), harrowing (0.25 m) and furrowing (0.35 m)	Deep plowing (0.40 m), harrowing (twice, 0.25 m) and furrowing (0.35 m)	Herbicide application, chisel plowing (0.40 m) and furrowing (0.35 m)
Soil Classification (Soil Survey Staff, 2010)	Typic Hapludox	Typic Kandiudox	Rhodic Eutrudox
Soil Texture	Sandy Clay Loam	Sandy Clay Loam	Clay
Month/Year			
Planted	Feb/2005	Apr/2005	Mar/2005
First harvest	June/2006	July/2006	Aug/2006
Second harvest	June/2007	July/2007	Aug/2007
Third harvest	July/2008	July/2008	July/2008
Fourth harvest	July/2009	July/2009	July/2009
Rainfall (mm)			
Plant cane	1,618	1,522	1,752
First ratoon	1,511	1,446	1,719
Second ratoon	1,212	1,366	1,372
Third ratoon	1,304	1,193	1,477
Average yield (Mg ha^{-1})			
Plant cane	138	146	150
First ratoon	80	119	80
Second ratoon	–*	107	58
Third ratoon	100	110	86

*Not available due to an accidental fire.

the experimental areas and daily rainfall data were obtained through rain gauges installed in the experimental sites. All sites have a historic with over than 30 years under sugarcane cultivation.

The field experiments were established on Feb 2005 in Pirassununga, Apr 2005 in Jaboticabal, and Mar 2005 in Pradópolis (Table 1). Details of soil tillage practices, fertilizer applications, weed control and other management practices adopted in the experimental fields can also be seen in Franco et al. (2010, 2011) for Pirassununga and Jaboticabal sites, and in Fortes et al. (2012) for Pradopolis site. In all experimental sites, the predominant regional climate is classified as Koppen Aw Tropical Savanna, according to Rolim et al. (2007).

The experimental design comprised four complete randomized blocks. The experiments were initially implemented to evaluate the effect of nitrogen fertilization (four N rates) on sugarcane below and aboveground biomass allocation and stalk yield. However, since the purpose of this study was not to evaluate the effect of nitrogen fertilization, all data were composed to evaluate dry mass and C inputs from post-harvest crop residues (straw and root system) produced by the variety SP81-3250 in three sugarcane fields throughout four consecutive crop seasons (plant cane and three ratoons). Therein, in each experiment measurements of aboveground (tops and dry leaves) and belowground biomass (roots and rhizomes) were performed in 16 plots (replicates). The plots were composed of 12 rows with 15 m length and 1.5 m of row-space.

Sampling and analyzes

The measurement of aboveground and belowground biomass was always carried out in the central area of the plots. In plant cane cycle, the sugarcane harvest was performed 16, 15 and 17 months after planting in Pirassununga, Jaboticabal and Pradopolis respectively. After the first harvest, the experimental sites were harvested successively after 12-month cycle until the fourth harvest (Table 1). Due to an accidental fire in Pirassununga in 2008, it was not possible to evaluate that cycle in this area. During the whole experimental period, one week before the mechanical harvest of sugarcane, the biometric measurements were performed to evaluate the biomass of the aboveground and belowground sugarcane compartments.

Table 2 – Chemical and physical characterization of soil at the experimental sites. Adapted from Franco et al. (2010, 2011) for Pirassununga and Jaboticabal and Otto (2012) for Pradópolis.

Soil horizon	Chemical attributes†										Soil texture‡			Bulk Density
	pH H_2O	SOM	P	K	Ca	Mg	Al	H+Al	CEC	BS	Sand	Silt	Clay	
		g kg⁻¹	mg kg⁻¹	mmol$_c$ kg⁻¹						%	g kg⁻¹			g cm⁻³
Pirassununga (Typic Eutrudox)														
Ap (0-0.2 m)	7.2	20	10	1.9	43	11	0	8	63.9	87	706	34	260	1.65
BA (0.20-0.44 m)	6.5	8	1	2.6	7	3	0	11	23.6	53	661	70	269	1.63
B_{W1} (0.44-0.81 m)	6.9	6	2	2.5	11	4	0	10	27.5	64	686	66	248	1.44
B_{W2} (0.81-1.50 m)	6.4	8	1	1.8	18	7	0	11	37.8	71	708	61	231	1.37
Jaboticabal (Typic Kandiudox)														
Ap (0-0.15 m)	6.3	23	10	3.6	18	13	0	17	51.6	67	661	54	285	1.31
A_2 (0.16-0.37 m)	6.0	16	11	2.2	9	5	2	18	34.2	47	651	53	296	1.46
BA (0.38-0.56 m)	5.1	11	3	1.2	2	1	8	31	35.2	12	603	50	347	1.39
B_{W1} (0.57-0.96 m)	5.6	8	1	0.9	3	1	3	20	24.9	20	583	46	371	1.21
B_{W2} (0.97-1.50 m)	5.9	7	1	3.5	2	1	0	9	15.5	42	578	53	369	1.24
Pradópolis (Rhodic Eutrudox)														
Ap (0-0.37 m)	5.4	30	36	1.7	29	9	1	59	98.7	40	135	227	638	1.30
Bw_1 (0-38-0.60 m)	5.5	15	6	0.2	22	6	0	30	58.2	48	117	195	688	1.33
Bw_2 (0.61-0.98 m)	6.0	10	2	0.2	20	5	0	23	48.2	52	117	170	713	1.32
Bw_3 (0.99-1.50 m)	6.8	8	1	0.2	16	4	0	19	39.1	51	112	175	713	1.38

†Soil chemical analysis according to Van Raij et al. (2001). SOM, soil organic matter; CEC, cation exchange capacity; BS, base saturation. ‡Sand, silt and clay obtained by the pipette method (Gee and Or, 2002).

For aboveground measurements, one sample was collected per plot, in which all plants within 2 m of sugarcane row were harvested and were separated in dry leaves, tops and stalks. The biomass (fresh matter) of each compartment was measured using a 0.02-kg precision field scale. Samples were crushed through a forage crusher and subsamples were hermetically sealed and taken to the laboratory where the subsamples were oven dried under forced circulation at 65 °C until they reached a constant dry weight, allowing obtaining the dry matter biomass production.

For belowground measurements, roots and rhizomes were analyzed separately. Root samples were collected in the same area previously used for aboveground measurements. A root sampling probe with a 5.5-cm internal diameter was used for sampling. This probe was lowered to a 0.6 m depth, divided into 0.2-m layers, in several positions in relation to the row (Figure 1). We chose to study soil depths lower than 0.6 m since 50 % of root biomass typically occurs in the upper 0.2-m soil layer and 85 % in the upper 0.6-m layer (Blackburn, 1984). The choice of using the probe method was based on the need to cause a minimal disturbance in the plot, considering the need to repeat the measurements over the years in the same plot. Also, the probe method provided similar results as compared to the monolith method (Otto et al., 2009), and higher throughput.

To evaluate rhizome biomass, the entire belowground plant components were collected in one meter of sugarcane row using a shovel to dig the soil. The rhizomes were separated manually from roots, washed and dried to determine dry matter of its compartments. Soil and root samples were sieved in the field using 2-mm sieves, and the roots were placed into plastic bags. Soil particles and pieces of roots were carefully removed from the rhizomes. In the laboratory, the roots were washed in water for the removal of soil particles. All samples were then oven dried under forced circulation at 65 °C,

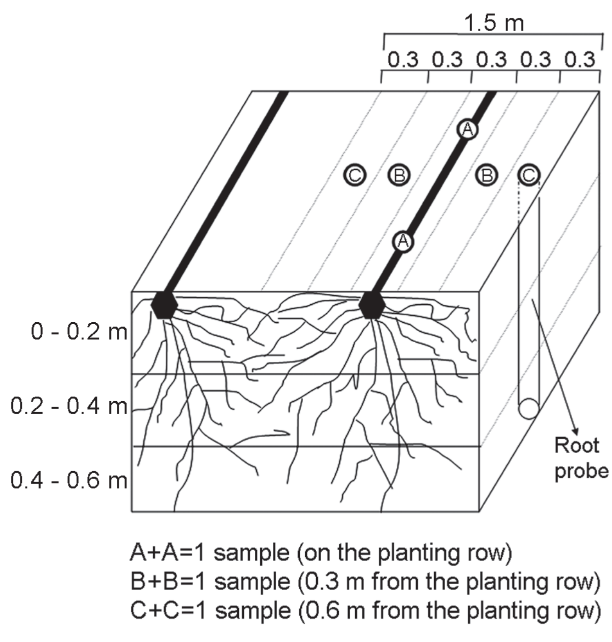

Figure 1 – Sugarcane root system sampling method (Source: Otto et al., 2009).

for the dry matter to be determined. The root biomass (Mg ha^{-1}) was calculated according to the methodology described by Otto et al. (2009).

Measurements of the roots have also taken over the cycles of plant cane and first ratoon in Pirassununga and Jaboticabal to measure the variation of root biomass over the crop cycle. The measurements of roots were performed, as previously described, during Oct 2005, Feb 2006, and June/July 2006, Dec 2006, Mar 2007, May 2007 and July 2007. Those evaluations did not include measurements of rhizome biomass.

Estimate of C addition by above and belowground biomass

We utilized the biomass of the below and aboveground obtained through the biometric measurements to estimate the input of C from straw and root system, and the C content in residues as measured by Fortes et al. (2011) in Pradopolis. According to this study, the straw (dry leaves and tops) had a C content of 440 g kg^{-1}, while it was 334 g kg^{-1} for the root system (roots and rhizomes).

A latter estimation was performed to calculate the contribution of straw and root system residues in supplying C to the soil in each agricultural year. This estimate was made using the C conversions ratio (rates of C crop residue transforming into SOC) obtained by Robertson and Thorburn (2007a) for aboveground biomass (13.0 %) and Bolinder et al. (1999) for belowground biomass (21.1 %).

Statistical analyses

Analysis of variance was processed considering the interaction among sites and plant compartments, separately for each crop cycle. When the F test showed significance by ANOVA, the Tukey test was performed ($p < 0.05$) to compare means.

Results and Discussion

Input of residues from straw and root system

There were differences ($p < 0.05$) between plant compartments and sites regarding biomass and C produced in the four sugarcane cycles (Table 3). Overall, the biomass production was higher during the plant-cane cycle, showing a tendency of reduction in subsequent ratoons. This is the expected trend since sugarcane yield is usually higher in the first crop cycle and decline with sugarcane aging. The reduction in biomass through the years was due the declining of the root system biomass, since the straw biomass (tops plus dry leaves) did not show substantial modification with sugarcane aging. Annual residue input (aboveground and belowground) ranged from 16.5 $\pm$ 1.6 to 19.5 $\pm$ 3.7 Mg DM ha^{-1} in Pirassununga, from 15.6 $\pm$ 3.0 to 21.7 $\pm$ 3.1 Mg DM ha^{-1} in Jaboticabal, and from 10.9 $\pm$ 1.4 to 20.8 $\pm$ 4.4 Mg DM ha^{-1} in Pradopolis. Dry leaves accounted for the largest dry mass input in all sites and years, while roots for the lowest input. The average production of aboveground biomass did not varied significantly among the areas, with values in the order of 12.4, 13.9 and 11.3 Mg DM ha^{-1} $year^{-1}$, respectively for Pirassununga, Jaboticabal and Pradopolis. Those amounts of straw are similar to the results obtained by Robertson and Thorburn (2007b) in Australia (7 to 12 Mg DM ha^{-1}), and by Oliveira et al. (1999) in Brazil (11 to 14 Mg DM ha^{-1}). The amount of straw on soil surface depends on the variety cultivated, timing of leaf shedding, sugarcane yield, efficiency of sugarcane harvester (Tufaile Neto, 2005), and also on the age of sugarcane fields.

The relationship between belowground and aboveground biomass (except stems) indicated higher participation of root system in plant-cane cycles than in older sugarcane cycles. In plant-cane fields, the root system contribution ranged from 34 to 37 %, while in the third ratoon values were in the order of 15 to 22 %. Annual biomass allocation from rhizome based on the four harvests, ranged from 1.8 $\pm$ 0.1 to 4.1 $\pm$ 0.6 Mg DM ha^{-1} $year^{-1}$ in Pirassununga, from 2.1 $\pm$ 0.2 to 5.2 $\pm$ 0.8 Mg DM ha^{-1} $year^{-1}$ in Jaboticabal, and from 1.7 $\pm$ 0.1 to 6.3 $\pm$ 0.7 Mg DM ha^{-1} $year^{-1}$ in Pradopolis. The rhizome compartment is not usually evaluated in the studies, and evidences presented herein indicate its amounts of DM in the harvest period are more pronounced than that of roots. However, little is known about the rate of rhizomes turnover and consequently how much of this material accounted in the sugarcane harvest is recycled during the next crop cycle. Besides being a significant source of C to the soil, rhizomes play an important role on the sugarcane ability to survive in harsh environments, mainly due its capability of tillering (Paterson, 2009). Added to this, a good ratoonability in sugarcane is undoubtedly linked to high tillering which, in turn, is linked to the amount and vitality of rhizomes (Matsuoka and Garcia, 2011). Moreover, Vitti et al. (2007) verified a positive correlation among nutrients reserves into rhizomes and stalk production of consecutive sugarcane ratoons.

Overall, taking the average values into account the three studied areas, the contribution of the belowground compartment (roots plus rhizomes) to total residual biomass was of 35 % in the plant-cane cycle, declining to 20 % in the 3rd ratoon (Figure 2). Similar results are expected for C allocation. This behavior is associated with the reduction of root growth due to its lower efficiency in ratoons, decreased crop productivity with age, and also with soil compaction process, as intense traffic of mechanized harvesting was practiced in the three sites. Mechanized sugarcane harvesting decreases the water infiltration rate and increases resistance to soil penetration and bulk density, especially when harvesting is performed on wet soils (Van Antwerpen et al., 2008), thus affecting root growth and development (Otto et al., 2011). The sugarcane root system growth is highly dependent on the soil physical conditions (Costa et al., 2007) and clay content (Aboyami, 1989). Aboyami (1989) observed that root biomass in a clayey soil was only 17 % of biomass for the sand soil in the plant-cane cycle, increasing to 59

Table 3 – Phytomass and carbon† in plant compartments over the sugarcane crop cycles at the three areas located in the Southeast Brazil. Values represent the mean of 16 replicates‡.

Plant compartments	Dry phytomass ($Mg\ ha^{-1}$)			Carbon ($Mg\ ha^{-1}$)		
	Pirassununga	Jaboticabal	Pradopolis	Pirassununga	Jaboticabal	Pradopolis
Plant cane						
Roots	2.58 ± 0.32 aC	2.10 ± 0.20 aD	1.33 ± 0.20 aD	0.86 ± 0.11 aC	0.70 ± 0.07 aC	0.44 ± 0.07 aC
Rhizomes	4.10 ± 0.56 bBC	5.23 ± 0.82 aB	6.28 ± 0.68 aB	1.37 ± 0.22 bC	1.75 ± 0.23 abB	2.10 ± 0.28 aB
Dry leaves	7.93 ± 0.36 bA	10.09 ± 0.53 aA	9.75 ± 0.59 aA	3.52 ± 0.16 bA	4.48 ± 0.26 aA	4.33 ± 0.23 aA
Tops	4.93 ± 0.22 aB	4.30 ± 0.20 aC	3.47 ± 0.31 aC	2.19 ± 0.10 aB	1.91 ± 0.14 abB	1.54 ± 0.07 bB
	19.54 ± 3.71	21.72 ± 3.07	20.83 ± 4.37	7.94 ± 1.51	8.84 ± 1.25	8.41 ± 1.76
LSD¶ sugarcane fields = 1.54				LSD sugarcane fields = 0.54		
LSD plant compartments = 1.69				LSD plant compartments = 0.64		
Coefficient of variation = 35 %				Coefficient of variation = 33 %		
1st ratoon						
Roots	2.90 ± 0.28 aC	2.03 ± 0.17 bC	0.85 ± 0.15 cD	0.97 ± 0.09 aC	0.68 ± 0.06 aD	0.28 ± 0.05 bD
Rhizomes	3.05 ± 0.22 bC	4.59 ± 0.26 aB	3.00 ± 0.24 bC	1.02 ± 0.07 bC	1.53 ± 0.11 aC	1.00 ± 0.08 bC
Dry leaves	7.45 ± 0.34 bA	9.59 ± 0.30 aA	6.47 ± 0.23 cA	3.31 ± 0.15 bA	4.26 ± 0.13 aA	2.87 ± 0.11 cA
Tops	4.18 ± 0.22 aB	4.99 ± 0.20 aB	4.37 ± 0.25 aB	1.86 ± 0.10 bB	2.22 ± 0.09 aB	1.94 ± 0.12 abB
Total	17.58 ± 2.24	21.20 ± 1.88	14.69 ± 1.90	7.15 ± 0.91	8.68 ± 0.77	6.10 ± 0.79
LSD sugarcane fields = 0.83				LSD sugarcane fields = 0.34		
LSD plant compartments = 0.91				LSD plant compartments = 0.37		
Coefficient of variation = 22 %				Coefficient of variation = 22 %		
2nd ratoon						
Roots	-§	1.37 ± 0.13 aD	0.77 ± 0.11 aC	-	0.46 ± 0.04 aD	0.26 ± 0.04 aC
Rhizomes	-	2.76 ± 0.28 aC	2.66 ± 0.26 aB	-	0.92 ± 0.09 aC	0.86 ± 0.10 aB
Dry leaves	-	9.80 ± 0.51 aA	5.44 ± 0.34 bA	-	4.35 ± 0.22 aA	2.42 ± 0.15 bA
Tops	-	4.88 ± 0.32 aB	2.05 ± 0.11 aB	-	2.17 ± 0.14 aB	0.91 ± 0.05 bC
Total	-	18.81 ± 2.68	10.92 ± 1.36	-	7.90 ± 1.13	4.47 ± 0.56
LSD sugarcane fields = 0.81				LSD sugarcane fields = 0.34		
LSD plant compartments = 1.07				LSD plant compartments = 0.45		
Coefficient of variation = 31 %				Coefficient of variation = 32 %		
3rd ratoon						
Roots	1.85 ± 0.16 aC	1.35 ± 0.09 abC	0.79 ± 0.10 bC	0.62 ± 0.05 aC	0.45 ± 0.03 aC	0.26 ± 0.03 aC
Rhizomes	1.82 ± 0.12 aC	2.11 ± 0.22 aC	1.71 ± 0.15 aC	0.61 ± 0.04 aC	0.70 ± 0.08 aC	0.57 ± 0.05 aC
Dry leaves	8.30 ± 0.26 aA	8.68 ± 0.53 aA	8.71 ± 0.44 aA	3.69 ± 0.12 aA	3.85 ± 0.23 aA	3.87 ± 0.20 aA
Tops	4.52 ± 0.15 aB	3.48 ± 0.14 bB	5.06 ± 0.27 aB	2.01 ± 0.07 aB	1.55 ± 0.06 bB	2.25 ± 0.12 aB
Total	16.49 ± 1.63	15.62 ± 3.01	16.27 ± 3.11	6.92 ± 0.68	6.55 ± 1.26	6.95 ± 1.33
LSD sugarcane fields = 0.85				LSD sugarcane fields = 0.36		
LSD plant compartments = 0.93				LSD plant compartments = 0.40		
Coefficient of variation = 25 %				Coefficient of variation = 26 %		

†Estimated using data of carbon contents obtained by Fortes et al. (2011) for the same area of study in Pradopolis. ‡Values in the same row (sugarcane fields) with the same small letters and values in the same column (plant compartments) with the same capital letters do not differ (Tukey test, $p < 0.05$). ¶LSD, least significant difference. §Data not collected due to an accidental fire in the experimental area.

% in the second cycle. In Pradopolis, the association of minimum tillage during sugarcane planting (Table 1) and higher clay content (Table 2), resulted in lower production of root biomass over the whole period of evaluation (plant cane and three ratoons).

Contribution of residues input to SOC

Understanding the production of dry mass by the different plant compartments (below and aboveground) and their potential in supplying SOC can facilitate the decision-making concerning the amount of straw to be left on the field for the sustainability of sugarcane crop. Robertson and Thorburn (2007a) evaluated the effect of maintaining sugarcane straw on soil C stocks and concluded that 87 % of this material was either respired by microorganisms or lost through leaching or runoff. The remaining (13 %) was incorporated into SOC. This results obtained by Robertson and Thorburn (2007a) are in agreement with others in literature, such as, Bolinder et al. (1999) that observed that 12 % of the aboveground residue of maize (*Zea mays* L.) crop was incorporated into SOC. However, according to Bolinder et al. (1999) the rate of C crop residue transforming into SOC resulting of the root system decomposition is higher than aboveground biomass. These authors evaluated the decomposition rates of belowground maize residues and observed that on average 21 % (ranging from 14 to 30 %) of C added to the soil by the root system is retained in the SOC. Corroborating this results, Gale and Cambardella (2000) observed that only 16 % of the oat straw was incorporated on SOM, while for roots system the C retention rate was 42 %. Santos et al. (2011) observed that root system inputs of several crops rotation systems (including wheat – *Triticum aestivum*, soybean – *Glycine max*, maize, oat – *Avena sativa*., vetch - *Vicia sativa*, ryegrass - *Lolium multiflorum* and alfalfa - *Medicago sativa*) resulted in a better correlation with the increase of SOC stocks in South

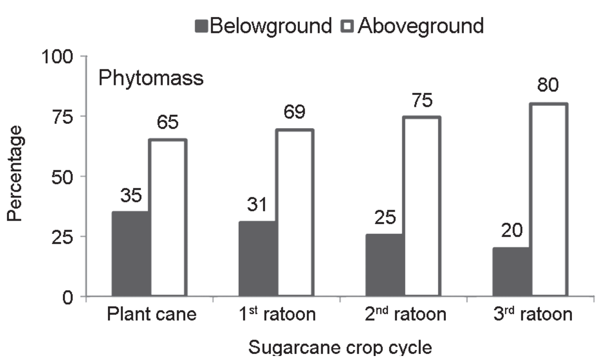

Figure 2 – Distribution of belowground (roots and rhizomes) and aboveground (dry leaves and tops) plant components biomass over the sugarcane crop cycle. Values represent the average of the three evaluated sites.

region of Brazil, indicating that roots seems to play a more relevant role in building up SOC stocks than shoot residue additions. This higher C retention rate through the root system when compared with aboveground crop residues can be explained by chemical composition, because roots have a higher concentration of phenolic and lignaceous compounds (Bolinder et al., 1999), and mainly because promoting soil aggregation, enhances the physical protection of C added directly into the soil (Oades, 1995). According to Lemus and Lal (2005), roots and rhizomes are a primary source of C to the soil in biofuel crops, and Anderson-Teixeira et al. (2009) point out that belowground allocation of C plays a critical role on driving changes in SOC in agricultural areas. Despite the several evidences in literature, however, no studies were found evaluating the real contribution of the sugarcane root system in supply C to the soil.

We estimated the contribution of sugarcane residues in supplying C to the soil by using the C conversions ratio (rates of C crop residue transforming into SOC) obtained in literature (Table 4). The root system (rhizomes plus roots) and straw (tops plus dry leaves) account for the incorporation of 0.2 to 0.5 and 0.4 to 0.8 Mg C ha^{-1} $year^{-1}$, respectively. Considering the total allocation of SOC (mean of four harvests) from aboveground and belowground compartments, a slight variation among the areas was observed, with values of 1.1, 1.2 and 1.0 Mg C ha^{-1} $year^{-1}$, respectively for Pirassununga, Jaboticabal and Pradopolis (on average, 1.1 Mg C ha^{-1} $year^{-1}$). This result is in the range of values found in literature, based in a review made by Cerri et al. (2011), which showed a mean annual C accumulation rate of 1.5 Mg ha^{-1} $year^{-1}$ (varying from 0.7 in sandy soils to 2.0 Mg ha^{-1} $year^{-1}$ in clayey soils) in the 0-0.3 m soil depth, in areas under green harvesting system.

Estimations were performed to provide an order of magnitude of the potential of above and belowground compartments to supply C to the soil. However, the contribution of the root system in supply C to the soil may be underestimated, because roots systems was quantified only in 0-60 cm soil layer and root exudates were not considered. A significant proportion of C results from rhizodeposition, i.e., the C released by roots as exudates (Kumar et al., 2006). Further, from 30 % to 60 % of C

Table 4 – Input of carbon by sugarcane root system (roots and rhizomes) and straw (dry leaves and tops) over the crop cycles†.

Crop cycles	Pirassununga			Jaboticabal			Pradopolis		
	Root system	Straw	Total	Root system	Straw	Total	Root system	Straw	Total
	Mg C ha^{-1}								
Plant cane	0.47	0.74	1.21	0.52	0.83	1.35	0.54	0.76	1.30
1st ratoon	0.42	0.67	1.09	0.47	0.84	1.31	0.27	0.63	0.89
2nd ratoon	-‡	-	-	0.29	0.85	1.14	0.24	0.43	0.67
3rd ratoon	0.26	0.74	1.00	0.24	0.7	0.94	0.18	0.80	0.98
Mean	0.38	0.72	1.10	0.38	0.81	1.19	0.31	0.66	0.97

†Estimates performed using C inputs described in Table 1 and the index of soil carbon retention obtained by Robertson and Thorburn (2007 a) for sugarcane straw and by Bolinder et al. (1999) for root system. ‡Data not collected due to an accidental fire.

photosynthesized by the plant is allocated to the root system, from which, 40 % to 70 % may be released in the soil by the rhizosphere (Lynch and Whipps, 1990). It is important to highlight that our estimates were obtained from extrapolations using results of DM production in field scale and C content and C retention rates obtained in the literature.

An important issue that needs to be evaluated in future studies is root turnover. After the harvest most of the sugarcane roots die and ratoon development depends on the formation of a new root system (Blackburn, 1984; Evans, 1964), but there is no consensus about it. For example, Ball-Coelho et al. (1992) concluded that root die-back after plant-cane harvest was less than reported in these previous studies and that not all root system is renewed. Ball-Coelho et al. (1992) hypothesized that the source of photosynthate to sustain the existing roots is a portion of the stem that remains alive after being cut. Thus, seems essential to develop other studies in order to evaluate, on-site, the turnover rate of roots and rhizomes and the real contribution of these plant compartments in supplying C to the soil.

Intra annual variations on roots biomass

Another important issue to be considered in studies that evaluate DM and C inputs from sugarcane root system is the quantification period. Overall, estimates are usually made during the sugarcane harvest, which can underestimate the real inputs of DM produced during the crop cycle, especially those from the roots. As an example of this behavior, roots DM of sugarcane was quantified in Pirassununga and Jaboticabal for the cycles of plant-cane and first ratoon (Figure 3). Both areas showed similar behaviors, and the highest root DM ($p < 0.05$) was obtained when the sugarcane crop was about 11 months old, coinciding with the period of high rainfall (Figure 3) and, therefore a higher soil moisture (Ghiberto et al. (2011).

Throughout plant-cane growth cycle was observed a reduction of root DM, coinciding with rainfall declining, sugarcane maturation, senescence of older leaves, translocation of sugar and the death of roots, which are incorporated into the soil. Variation in root DM over the growth cycle was higher in plant-cane than in first ratoon. Over the cycle of plant-cane, root DM was twice higher than those obtained in the sugarcane harvest in Pirassununga, and three times higher than those obtained in Jaboticabal. Sugarcane roots in ratoons are less robust since they are more susceptible to soil compaction (caused by machinery traffic), have a shorter growth cycle (of about 12 months) and, because the ratoon sprouting occurs close to the soil surface, their roots are more superficial than those of the plant-cane (Alvarez et al., 2000).

Input of roots to the soil can be underestimated when evaluated only during harvesting. Taking into account the maximum production of roots (10 to 12 months after sugarcane planting), a higher contribution of roots in supply C to the soil was observed in plant-cane cycle. A comparison between estimates obtained at the harvesting period (Table 3) indicated that the contribution of the root system (rhizomes and roots) to organic matter input increased from 28 to 35 % in Pirassununga, and from 28 to 39 % in Jaboticabal (Figure 4). This means that, if the eval-

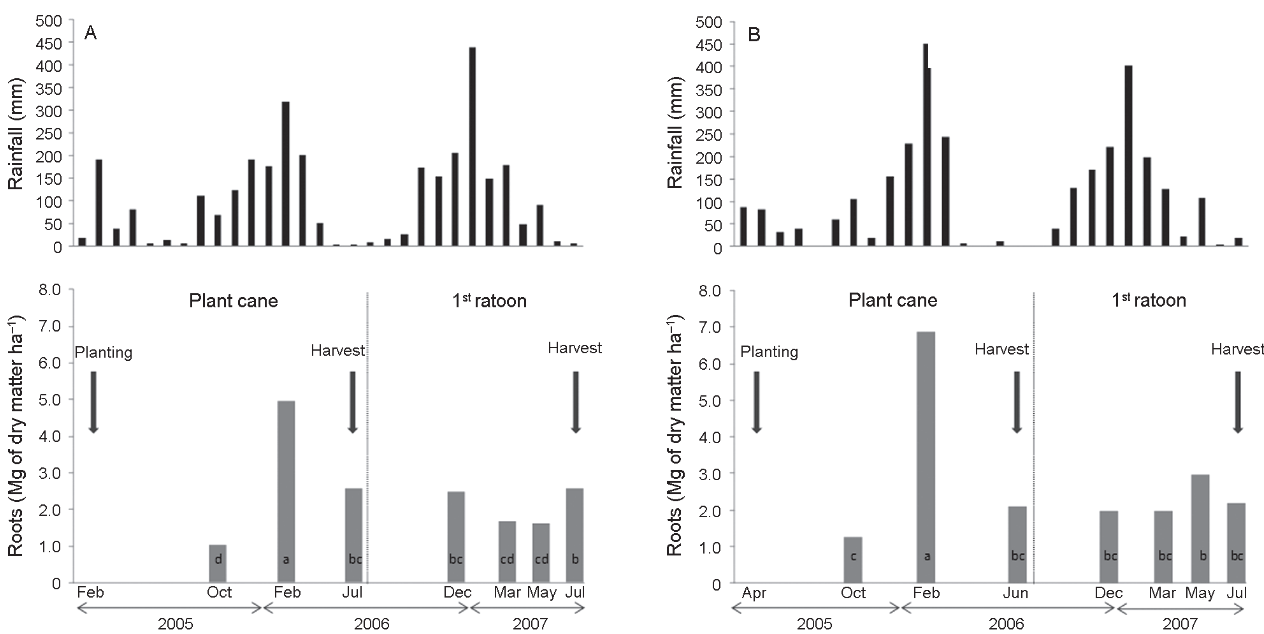

Figure 3 – Rainfall and amount of roots in the 0-60 cm depth soil during the plant-cane cycle and first ratoon in Pirassununga (A) and Jaboticabal (B). Values represent the mean of 16 replicates. Values with the same letters do not differ (Tukey test, $p < 0.05$).

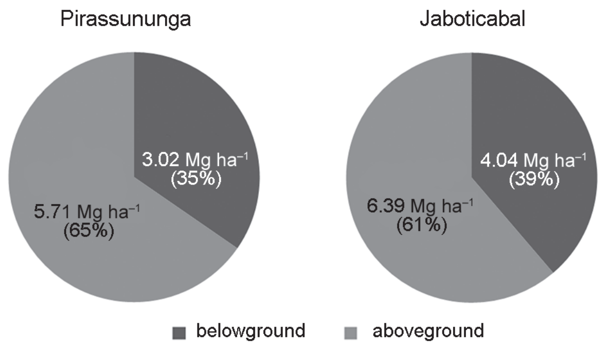

Figure 4 – Amount of C produced by below and aboveground plant compartments, considering the season of greater root biomass in areas under plant-cane cycles located in Pirassununga and Jaboticabal. Values represent the mean of 16 replicates.

uation of root DM is performed only during the harvesting period, the potential C input from the root system will be underestimated by 7 % and 11 % for Pirassununga and Jaboticabal, respectively. Therefore, it seems important to evaluate the root system throughout the sugarcane crop cycle in order to estimate adequately the contribution of root system to supply C to the soil and consequently improve the SOC sequestration in sugarcane fields.

Conclusions

Sugarcane aboveground plant compartments comprises the main source of crop residues to the soil, twofold higher than the produced by belowground plant components. Estimates revealed the potential incorporation of 1.1 Mg C ha^{-1} $year^{-1}$ into SOC by sugarcane residues, 33 % of which from root system and 67 % from straw. Despite root system being an important source of organic matter to the soil in sugarcane fields, aboveground plant compartments were the main contributor to supply C to the soil. The hypothesis of this study was rejected and there is no evidence that input of C from root system can mitigate the negative effect of removing straw (even partially) from sugarcane fields for industrial purposes.

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