ORGANIC CARBON STOCKS IN SOILS PLANTED TO SUGARCANE IN THE MID-SOUTH REGION OF BRAZIL: A SUMMARY OF CTC'S DATA, 1990 -2009

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Indexing terms: sugar cane, soil organic carbon, clay content, soil properties mapping.

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CONTENTS

SOIL MAPPING IN SUGAR CANE CULTIVATION AREAS IN MID SOUTH BRAZIL

This report was prepared by Centro de Tecnologia Canavieira - CTC, Piracicaba –Brazil, successor of Centro de Tecnologia Copersucar founded in 1969. The present CTC is a nationally and internationally well known private organization dedicated to research and technology transfer to the agro-industrial sector of sugarcane. The CTC has as its owners 154 sugar mills, cane growers and distilleries of ethanol. This group was responsible for a production of 306 million tonnes of sugarcane in the 2010/2011 harvest season.

A comprehensive soil mapping program was established by CTC at the beginning of the 80's following the commercial release of the first varieties of its sugar cane breeding program, started in 1969. The CTC soil survey program was created due to a lack of detailed soil information for planting sugarcane varieties on the properties of its associated members (COPERSUCAR, 1982) and also due to the expansion of Pro Alcohol program.

A team of soil survey technicians was established to create soil maps and also disseminate the use of soil properties knowledge for varietal allocation. It was important to establish, alongside the work of soil survey, a new specific nomenclature of soil types in a clear and easy way to be used by the sugar cane growers.

Based on the criteria of the Agronomic Institute of Campinas – IAC (OLIVEIRA; MENK; ROTTA, 1979; OLIVEIRA ET al., 1982) and Brazilian Society of Soil Science (CAMARGO; KAMT; KAUFFMAN, 1987) a "Soil Classification Key" was created by CTC researchers such that a soil type was identified by a single and simple acronym.

In the CTC methodology for soil mapping, samples were collected using an auger inside the cane fields. The soil was collected at depths of 0 to 0.25 m, 0.25 to 0.50 m e 0.80 to 1.00 m. In trenches the soil was sampled up to 2.00 m depth. The soil analyses were sent to labs accredited by the Instituto Agronomico de Campinas – IAC, a standardized government institute for soil analyses. The analyzed items include: organic matter, water pH, KCl, pH, clay, silt, fine sand, coarse sand, P (phosphorus), Na (sodium), K (potassium), Ca (calcium), Mg (magnesium), Al (aluminum) and H (hydrogen) (OLIVEIRA; MENK; ROTTA, 1979; CAMARGO et al., 1986, 2009). In this report of soil analyses, several items were calculated such as: delta pH, sum of bases, CEC (Cation Exchange Capacity), base saturation and aluminum saturation. These calculated values are used for soil classification according to the CTC soil key. Data from samples taken from soil profiles were added to this list, such as soil density (particulate and bulk) for each soil horizon.

A specific methodology for the interpretation of soil maps in sugarcane areas was created in the years of 1992 to 1994 using the maps and the CTC sugarcane yield data bank. This work has resulted in the first version of a land classification system named "Production Environments" (JOAQUIM et al., 1994, 1997). More than 300 soil types of the CTC soil classification key surveyed on plantations farms are now grouped in five ranges of yield potential (A, B, C, D and E) the Environments for Production. The soils of the environment of production "A" are the top yield potential and the soils of the environment of production "E" are the lowest yield potential. With the application of this concept it is possible to directly allocate sugarcane varieties and explore the full genetic potential incorporated by the breeding programs (JOAQUIM et al., 1994, 1997; DONZELLI; JOAQUIM; BELLINASO, 2005).

In the harvest season of 2002/2003 CTC researchers started a study of yield, not only as a function of soil, but also of climatic conditions. So by the end of harvest season of 2008/2009 CTC released the second generation of Environments of Production called now " Edaphoclimatic Environments for Production" which is a combination of data on soil, climate and sugarcane yield (BERTOLANI; JOAQUIM; DONZELLI, 2009; DONZELLI; JOAQUIM; BERTOLANI, 2010). From this point all varieties released by CTC Breeding Program are selected under a specific Edaphoclimatic Environment for Production in different regions of sugarcane in Brazil.

At present, the CTC soil scientists are surveying in detail 300,000 ha per year, which is used to generate soil maps appropriate for the present technological level of Brazilian sugar industry. The CTC soil team is spread around the Brazilian sugarcane regions with a concentration in the Center South Region. The mapped area under this system accounts in the 2010/2011 harvest season for approximately 1.5 million hectares.

From the 300,000 ha of farms surveyed 15,000 soil samples are taken at 3 depths and 675,000 physical and chemical analyses of different soil types are stored in the CTC data banks. This data is used for many different research and development projects. Due to its importance for the evaluation of greenhouse emissions derived from direct land use change (in the expansion of the sugar cane area) one of the studies included the establishment of a correlation between soil carbon amounts as a function of clay content in the sugar cane plantations. The results are discussed in this report as an example of the research potential of this comprehensive CTC Soil Survey Program.

SUMMARY: SOIL ORGANIC CARBON DATA

The carbon in the soil is important to improve its chemical, physical (aggregate stability) and biological characteristics, and for a given land cover and cultivation procedures, its concentration varies as a function of the soil texture and depth. The study described herein is intended to quantify the carbon stock in the soil in tonnes (Mg) per hectare at two depths: 0-25 cm and 25-50 cm, and also a consolidated data for 0-50 cm, in sugarcane fields in the Brazilian Mid-South (States of Sao Paulo, Parana, Mato Grosso do Sul, Minas Gerais and Goiás). For such a purpose, the percentage of organic carbon in the soil was correlated to the percentage of clay, and the soil density was also determined in different textures that were used in calculation of the carbon storage in the soil.

The study used the data related to the soil samples collected in the depths of 0-25 cm and 25-50 cm on 27,552 sites (sampling sites) resulting from the soil surveys conducted by Centro de Tecnologia Canavieira – CTC (Cane Technology Center), in their Members' fields located in the Mid-South region of Brazil, from 1990 to 2009 covering an area of 1.5 million ha planted with sugarcane. Such samples were collected in 78 Mills and 8 Cane Growers Associations in the states of São Paulo, Paraná, Mato Grosso do Sul, Minas Gerais and Goiás.

Through a simple regression equation, the content of organic carbon in the soil was correlated as a function of the clay content in both depths.

To quantify the density, in g/cm^3, as a function of the texture, the data from 292 soil profiles (sites) of 27 mills in the depths of 0-25 cm and 25-50 cm were used.

To assess the Carbon Stock, in tonnes per hectare, in the soils cultivated with sugarcane in the Mid-South of Brazil, the carbon percentage and the average density were used based on the texture levels in the depths of 0-25 cm and 25-50 cm (0-50 cm).

The findings showed that there is an increase in the soil carbon upon the increase in clay in the soils cultivated with sugarcane in the Mid-South of Brazil, whereas the percentage of carbon decreases in depth for the same percentage of clay. A new interval of carbon percentage can be proposed for tropical soils cultivated with sugarcane; between 0.2% and less than 5% for the depth of 0-25 cm.

The simple regression equation showed a reverse correlation for the soil bulk density, i.e. the clay percentage goes up as the soil density goes down, with very similar values in both depths.

Based on the carbon percentage and the soil density, the carbon stock was determined for two depths (0-25cm; 25-50 cm) and also for the consolidated depth of 0-50 cm. The findings showed values for carbon stored in the soil with sugarcane compatible with soil under forestry; the range values were: 29.5 t/ha to 59.1 t/ha for the depth of 0-25 cm. The lowest value was found in very sandy soils and the highest values on high clay soils. The same trends were found for the depth of 25-50 cm, with a range for soil carbon stocks from 20.2 t/ha to 40.3 t/ha. The overall values of carbon stock for 0-50 cm depth were 49.7 t/ha to 99.4 t/ha.

OBJECTIVE

The objective of this study was to estimate mean soil C stocks in this region as a function of soil texture using soil type, bulk density and C content of over 27,500 soil samples taken from cane fields over a period of 20 years.

INTRODUCTION

The area in Brazil planted to sugarcane has expanded from 5 Mha in 2002 to almost 9 Mha today and somewhat over half of this area is used for the production of ethanol for biofuel. Brazilian bioethanol produced from sugarcane has recently been classified by the US environmental protection agency (EPA 2010) as an Advanced Biofuel owing to its high greenhouse gas (GHG) mitigation potential, estimated as approximately 60 % and 90% (without and with residue utilization, respectively). The production of this biofuel requires very low fossil fuel inputs mainly because all factory processing is fuelled by bagasse (MACEDO, 1998). While recent estimates of fossil fuel use in, and GHG emissions from, the agricultural and processing phases are well documented (MACEDO; SEABRA; SILVA, 2008; BODDEY et al., 2008) and accepted internationally, the same is not true of the GHG emissions involved in the change in land use when new areas of cane are planted.

More than 80 % of the expansion of sugarcane since 2002 in Brazil is in the Central South region (the States of São Paulo - SP, Paraná - PR, Mato Grosso do Sul - MS, Goiás - GO and Minas

Gerais - MG) and to date only a few isolated data of the soil carbon stocks under this crop in the region have been published,

Recent studies have demonstrated the importance of organic carbon in the soil, as well as its maintenance in the land ecosystem in order to prevent or mitigate severe climate changes.

In tropical soils with appropriate management, the carbon contents in the soil can be similar to or higher than those in regions under temperate weather. This is due to the fact soils with higher level of weathering evidence Fe and Al oxides in their mineralogical constitution, demonstrating significant interaction with organic matter and consequent higher stability of the organic fraction to the decomposition by microorganisms in comparison with soils with lower degree of weathering (PARFITT et al., 1997).

Canellas et al. (2003) demonstrated that, in areas of green cane harvesting, in addition to the direct impacts from the organic matter preservation, which naturally benefits the carbon concentration, the field is subject to a longer turnover time, whereas, in some areas, the average time for field turnover is of four years; such time is the double at least in green cane harvesting areas.

The areas converted to cane recently, and in the near future, were/are mostly low-productivity pasture or land with annual crops, citrus or coffee. The new areas used in the last decade are mostly in areas of the Cerrado biome, although almost entirely implemented over pasture lands and annual crops (not native vegetation) (NASSAR et al., 2008). This trend has been verified with data from several sources: Satellite images (Landsat and CBERS, since 2003) (NASSAR et al., 2008; SUGAWARA et al. 2008); in 2007 and 2008, the cane area growth used 98% from pasture (45%) and annual crops (53%); 1.3% from Citrus; less than 1% from arboreal vegetation. Detailed survey from the CONAB (MAPA/DCAA) (CONAB 2008) for the changes in land use (2007 to 2008); covering all sugar cane producing units (349, in 19 states): 89.5 % came from pasture and annual crops; 5.4% from 8 permanent crops; other, 3.7%; “new areas” (not all native vegetation): less than 1.5%.

One problem using the IPCC Tier 1 recommendations (IPCC, 2006) for calculating the change in soil C stocks when there is a land use change to sugarcane, is that these recommendations cover only annual or perennial crops. In Brazil sugarcane is only replanted every 5 or 6 years, or occasionally more, and apart from the first harvest, when typically the cane cut after 18 months of growth, the ratoon crops are harvested annually. The largest soil C loss is caused by the intense tillage at re-planting, but subsequently this high-yielding C4 crop facilitates the recuperation of soil C (VALLIS et al., 1996). The gradual increase over the years of cane yields (a mean increase of ~2 % per year), the recent change in practice from pre-harvest burning to trash conservation and the introduction of no-till planting (LA SCALA; BOLONHESI; PEREIRA,2006) will all contribute to increasing soil C stocks. The CTC's soil mapping program continues, and in the next years it will show the effect of the new practices on soil carbon stocks; and selecting data for sugar plantations older than 20 years (a large portion of the mapped area) will lead to better values for equilibrium soil C stocks.

MATERIALS AND METHODS

The soil samples were taken from an area comprising 1.2 Mha belonging to 78 mills and 8 cane-growers associations, members of the cooperative affiliated to the Centre for Sugarcane Technology (CTC, Piracicaba, SP – www.ctc.com.br). The soil samples destined for carbon analysis were taken with an auger at 27,552 points for three depth intervals (0-25, 25-50 and 80-100 cm) conducted by Centro de Tecnologia Canavieira – CTC between 1990 and 2009, as part of a comprehensive soil mapping program needed to optimize the allocation of cane varieties. An effort was made to take samples representative of all fields under cane, and at each site the soil type was described under the Brazilian classification down to the equivalent of fourth level (subgroups) in the US Soil Taxonomy classification. Soil samples were analyzed for organic C, pH, P, K, Al, Ca, Mg , H, clay, silt and sandy using the standard methodology of the Institute Agronomic of Campinas (OLIVEIRA; MENK; ROTTA, 1979; CAMARGO et al., 1986, 2009) only in laboratories accredited by this institute. At a smaller number of sites (292) chosen to represent all soil types and textures within the area, sampling pits were opened to a depth of 2 m for the evaluation of soil density as well as the parameters measured for the other samples. The augered samples were grouped together with the pit samples by soil type, texture and fertility indices, and the soil bulk density data of the latter were used to calculate soil C stocks for the 0- 25, 25-50 and 0-50 cm depth intervals.

Within the area sampled the following soils types (US Soil Taxonomy) were encountered: Oxisols, Alfisols, Ultisols, Inceptisols and Entisols (Oxisols 75.1 %, Alfisols/Ultisols 17.3 %, Entisols/Inceptisols 7.7%).

To assess the carbon stock in sugarcane soils it was necessary to establish a correlation between the carbon percentages as a function of the clay percentage in sugarcane cultivation soils. The data of soil samples collected 0-25 cm and 25-50 cm deep on 27,552 sites (sample sites) were used, related to the soil surveys (1.2 million ha) conducted by Centro de Tecnologia Canavieira – CTC between 1990 and 2009. One must point out that such analyses were carried out by several accredited laboratories and collected by different specialized technicians. The samples were collected in 78 Mills and 8 Cane Growers Associations in Brazil's Mid-South, represented by the States of São Paulo, Paraná, Mato Grosso do Sul, Minas Gerais and Goiás (Figure 1), covering an area of 1.2 Mha planted with sugarcane. The State of São Paulo, relying on the larger number of mills (45) and Growers' Associations (7), had the highest number of sample sites – 18,110 sites. Paraná on 3,484 sites in 11 mills, Mato Grosso do Sul on 2,257 sites in 7 mills, Minas Gerais on 1,942 sites in 7 mills and one growers association and Goiás had 1,759 sites in 8 mills.

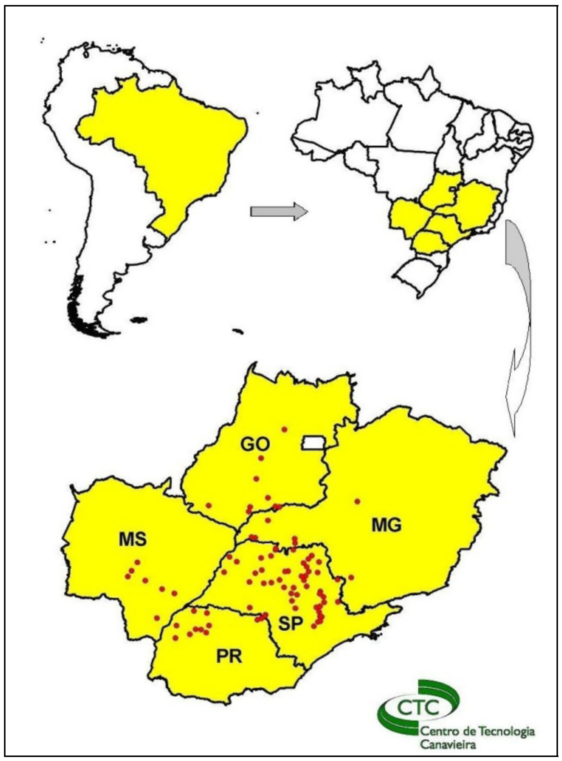

Figure 1 - Location of the Mills and Cane Growers Associations in the Mid-South region of Brazil where the soil samples were collected.

The clay and carbon results used in this case study came from soil samples collected in areas with different use time of sugarcane, which can vary from one year to more than 50 years, in cane areas harvested green (without burning) or burned.

To calculate the soil carbon stocks a simple regression equation was generated in order to calculate the quantity of carbon and the soil density, in g/cm^3, as a function of texture, in the soils of the Brazilian Mid-South. To calculate the concentration of carbon, all the soil samples (27,552) collected in the five Brazilian States at 0-25 cm and 25-50 cm deep were used; and to quantify the soil density as a function of texture, the data from 292 soil profiles (trenches) in 27 mills, at depths of 0-25 cm and 25-50 cm were also used.

To calculate the soil carbon stocks, in tons per hectare, under the sugarcane crop of the Mid-South Brazil, the carbon percentage (%) and the average density found per soil texture were used for both depths intervals of 0-25 cm and 25-50 cm and for the consolidated data for the depth of 0-50 cm.

According to the Brazilian soil key classification (EMBRAPA, 2006), soil samples collected can be categorized into the following soil classes of the second category level (sub orders): Red Latosol, Red-Yellow Latosol, Yellow Latosol, Red Nitosol, Haplic Nitosol, Red Argisol, Red-Yellow Argisol, Yellow Argisol, Quartzarenic Neosol, Litholic Neosol, Haplic Cambisol and Haplic Plintosol.

FINDINGS AND DISCUSSION

Percentage of organic carbon in the soil as a function of the percentage clay

The joint analysis of the data sampled on 27,552 sites in the sugarcane plantation regions in five Mid-South States of Brazil generated a single simple regression equation that relates the contents (percentage) of carbon and clay in the soil for the depths of 0-25 cm and 25-50 cm. The simple regression equations between percentage organic carbon (y) and percentage clay (x), and the correlation coefficient (R^2) can be seen in Table 1.

Table 1 - Simple regression equation between organic carbon (y) and clay (x), both in %, and the correlation coefficient (R^2) in sugarcane cultivation soils in the Brazilian Mid-South.

Brazilian Region	Depth	Equation	R^2
Mid-South	0-25 cm	y=0.0181x+5.511	0.43
	25-50 cm	y=0.0132x+3.656	0.40

Using the criterion of a cation exchange capacity (CEC) of less than 27 cmol kg soil^{-1}, 95.5 % of the augered soil samples were classified as low activity clay (LAC) soils. Only very few samples contained over 30 g C kg^{-1} in the 0-25 cm depth interval (Fig. 2) or over 20 g C kg^{-1} at 25-50 cm (fig 3). As was to be expected there was a clear, highly significant (P<0.001) positive relationship between soil C concentration and clay content (FELLER; BEARE, 1997), but the regression coefficients (r^2) were only 0.43 and 0.40 for the 0-25 and 25-50 cm depth intervals, respectively.

Some of the plantations have been growing cane for over 50 years and some were newer areas. When the sampling began (1990) virtually all cane in the region was burned before harvest. In recent years green-cane harvesting has been introduced on a large scale such that today in this region approximately 53 % of the area is no longer burned. The conversion to green cane harvesting (trash conservation) has been shown to increase soil C stocks (GALDOS et al., 2009; PINHEIRO et al, 2010). In this sampling no information on the age of the plantation, previous land-use, fertilizer use, burning or green cane harvesting or other management details were recorded. This explains why the regression coefficients of clay versus C content are lower than might be expected.

The highest correlation was observed in the soils of the first layer (0-25 cm) with R^2=0.43, evidencing medium dispersion of the data, and the lowest correlation in the second layer (25-50 cm) with R^2=0.40.

These management practices are probably responsible for majority of the differences found in this study case. For both depths the pattern of the carbon levels in the soil concerning the texture ranges in the five Brazilian States shows that, despite existing trends, there are other impacting factors. It was not possible to establish a direct relation, cause/effect with the obtained data, as for the soil samples collected over approximately 19 years the sugarcane management was not described. This management can vary in time and quantity from site to site. The application of chemical fertilizers, liming, application of industrial byproducts (filter cake, ashes, carbon black and vinasse), or even sugarcane straw, can affect the pattern of the contents of carbon in the soil and can also partially explain the data dispersion. As observed by Suman et al., (2009), the changes in the management and maintenance of cultivation residues can help increase and restore the levels of organic carbon in the soil, the sustainability of the production system and soil use.

According to Albers et al., (2008), carbon contents between 10 and 50 g kg^{-1} are found in the soils under tropical weather; depending upon the environmental conditions, soil texture and vegetation type. Their dynamics impacted by the C-cycling controlling mechanisms, and it is an important contributor to the chemical and physical aspects of the soil. Such observation proved to be true for the highest value, where it was found that all the samples had carbon contents below 50 g kg^{-1}. A new interval can be proposed for tropical soils under semi perennial crops such as sugarcane, with the variation between 2 g kg^{-1} and less than 50 g kg^{-1} for the depth of 0-25 cm (Figures 2 and 3).

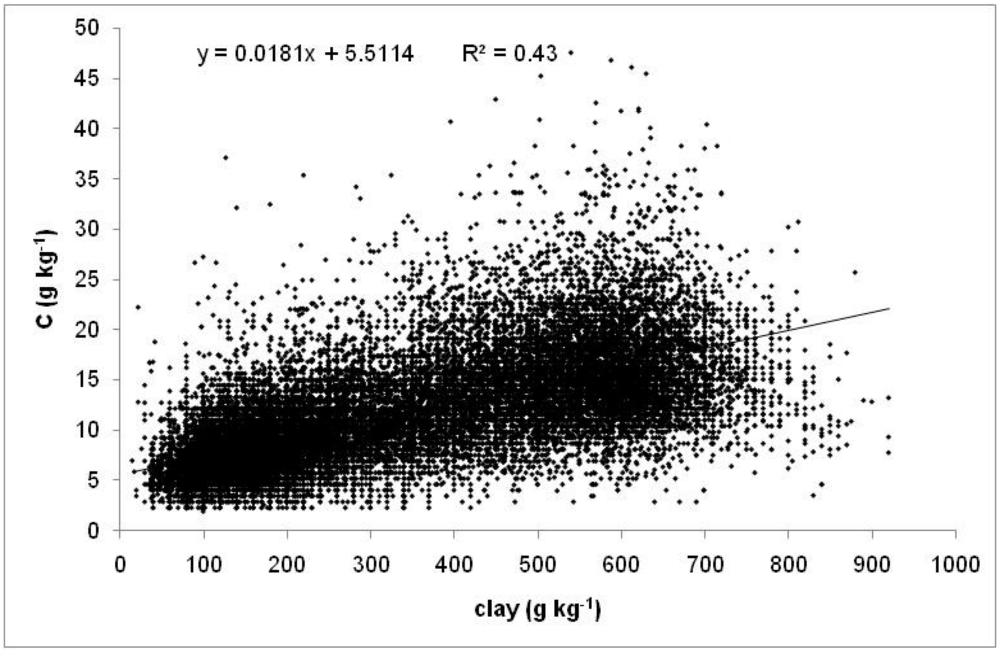

Figure 2 –Percentage of organic carbon as a function of percentage clay for the depth of 0-25 cm in soil samples of the Mid-South States Brazil.

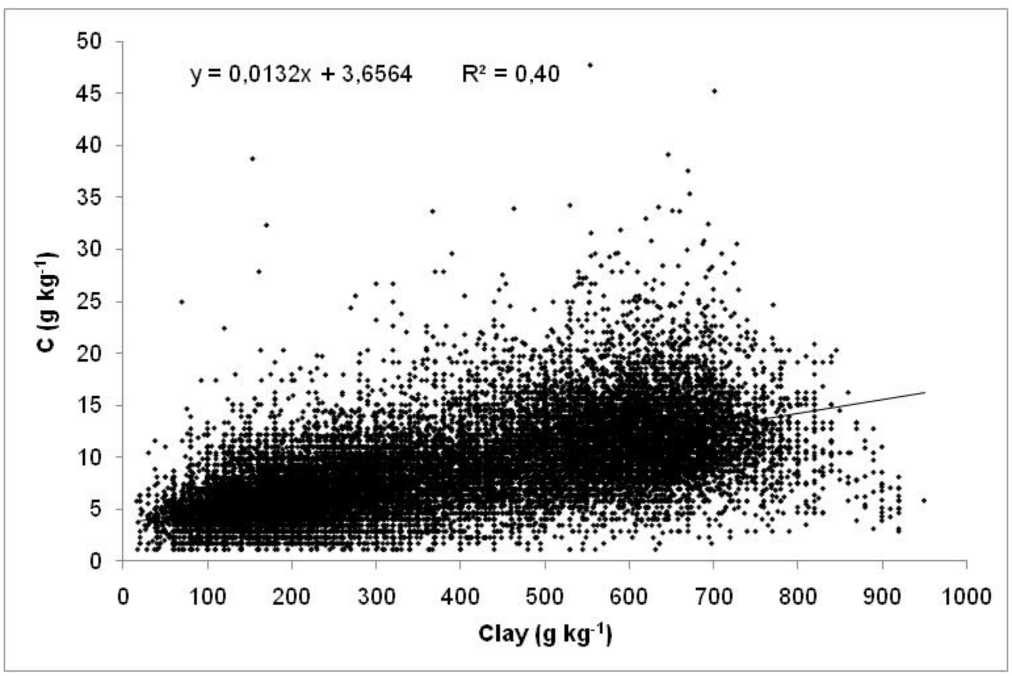

Figure 3 –Percentage of organic carbon as a function of percentage clay for the depth of 25-50 cm in soil samples of the Mid-South States Brazil.

Based on the simple regression equation, the carbon percentage as a function of the clay percentage 0-25 cm and 25-50 cm deep (Table 2 and Figure 4) was calculated. The average for carbon (g kg^{-1}) obtained in 27,552 soil samples for 0-25 cm is 11.4 g kg^{-1} of soil and for 25-50 cm is 8.4g kg^{-1} of soil. The average clay contents for 0-25 cm is 325 g kg^{-1} of soil and for 25-50 cm is 357g kg^{-1} of soil, and also were obtained in the 27,552 soil samples.

According to Milles; Meyer & Van Antwerpen (2008), the quantity of organic carbon rises as a function of the quantity of clay in the soil, owing to the protection clay provides against organic matter oxidation. Schimel et al. (1994) and Silver et al. (2000) also found out a positive correlation between the soil carbon contents and the clay contents. Such relation was also observed in this study. One can see (Table 2 and Figure 4) an increase in the carbon quantity upon the increase in the clay contents, in both depths analyzed.

Table 2 – Carbon (g kg^{-1}) as a function of the clay percentage (g kg^{-1}), 0-25 cm and 25-50 cm deep, in the soils of the Mid-South States cultivated with sugarcane.

Depth	**Clay (g kg^{-1})**							
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**
0-25 cm	7.32	9.13	10.94	12.75	14.56	16.37	18.12	19.99
25-50 cm	4.98	6.30	7.62	8.94	10.26	11.58	12.90	14.22

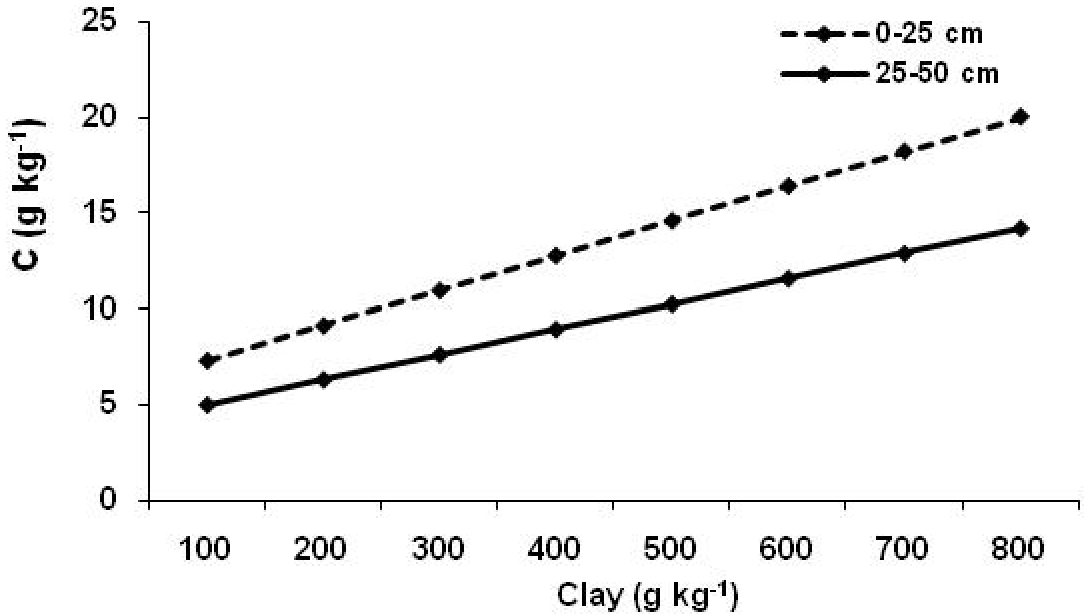

Figure 4 - Distribution of the organic carbon contents (%) as a function of the clay contents (g kg^{-1}) in the soil of Mid-South States, 0-25 cm and 25-50 cm deep.

Tables 3 and 4 show the averages and the confidence interval (range including 90% of the data) for both clay and Carbon contents, for each clay interval (with 100 g kg^{-1} each) from zero to 800 g kg^{-1}. Depths of 0-25 cm and 25-50 cm, respectively, are considered in Tables 3 and 4.

Table 3 – Average Carbon (g kg^{-1}) and clay (g kg^{-1}), in clay intervals (100 g kg^{-1} each) from 0 to 800 g kg^{-1}; and confidence interval, for the 0-25 cm depth, in the soils of the Mid-South States cultivated with sugarcane.

Clay ranges (g kg^{-1})	**Data**					
	Clay (g kg^{-1})			**Carbon** (g kg^{-1})		
	Average	**90 % confidence interval of the data**		**Average**	**90 % confidence interval of the data**	
		Lower limit	**Higher limit**		**Lower limit**	**Higher |limit**
000-100	81.4	53.0	100.0	6.7	2.5	10.9
100.1-200	150.7	105.4	196.0	8.0	3.2	12.7
200.1-300	245.9	200.1	292.1	10.2	4.1	16.2
300.1-400	354.4	307.8	400.0	12. 5	4.9	20.0
400.1-500	454.4	406.4	500.0	14.5	6.5	22.4
500.1-600	554.7	507.2	600.0	16.0	7.6	24.3
600.1-700	643.3	600.1	689.6	16.8	8.0	25.5
700.1-800	738.6	700.1	783.8	16.1	8.4	23.7

Table 4 – Average Carbon (g kg^{-1}) and clay (g kg^{-1}), in clay intervals (100 g kg^{-1} each) from 0 to 800 g kg^{-1}; and confidence interval, for the 25-50 cm depth, in the soils of the Mid-South States cultivated with sugarcane.

Clay ranges (g kg^{-1})	**Data**					
	Clay g kg^{-1}			**Carbon** g kg^{-1}		
	Average	**90 % confidence interval of the data**		**Average**	**90 % confidence interval of the data**	
		Lower limit	**Higher limit**		**Lower limit**	**Higher limit**
000-100	81.1	**49.**	100.	4.9	1.2	**8.6**
100.1-200	157.9	113.	200.	5.7	1.8	9.7
200.1-300	246.9	201.	293.	6.7	2.3	11.1
300.1-400	350.5	303.	398.	8.1	2.2	13.9
400.1-500	454.3	406.	500.	10.0	3.6	16.9
500.1-600	554.5	507.	600.	11.5	5.0	18.1
600.1-700	647.2	601.	693.	12.4	5.5	19.4
700.1-800	739.4	700.	785.	12.3	6.0	18.7

The soil density as a function of the clay percentage in the Brazilian Mid-South soils.

To calculate the soil density as a function of the clay percentage, the data related to the 292 profiles collected in sugarcane areas were used (Figure 5 and 6). The joint analysis of the data generated a simple regression equation for the depths of 0-25 cm and 25-50 cm. Table 5 shows such equation, correlating the soil density (y), in Mg m^{-3} and clay (x), concentration (g kg^{-1}), and the correlation coefficient (R^2). The highest correlation was observed in the soils of the second layer, R^2=0.57, showing a medium dispersion of the data, whereas the lowest correlation was observed in the first layer, R^2=0.47, this lower correlation occurs due to the higher changes impacted by the management in such layer, as it was previously discussed.

The soil bulk density is strongly related to soil texture and in this study, in the 0-25 cm depth interval, the bulk density decreased with increasing clay content according to a linear relationship of $y = - 0.0006x + 1.681$ (r^2 = 0.47 Fig. 3).

Table 5 - Simple regression equation between soil density (y), in Mg m^{-3} and clay (x), in g kg^{-1}, and the correlation coefficient (R^2) in sugarcane cultivation soils, in the Brazilian Mid-South.

Brazilian Region	Depth	Equation	R^2
Mid-South	0-25 cm	y=-0.0006x+1.681	0.47
	25-50 cm	y=-0.0070x+1.6965	0.57

Figure 5 and 6 shows the distribution of soil density as a function of clay content in the soil profiles surveyed in the depths of 0-25 cm and 25-50 cm.

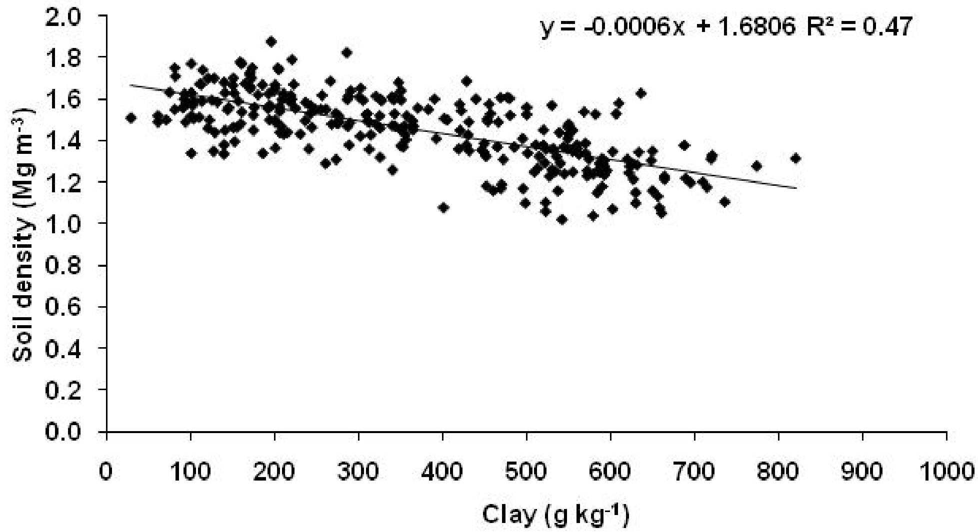

Figure 5 - Soil density as a function of clay in the 292 samples for 0-25 cm in the soils of the Mid-South States.

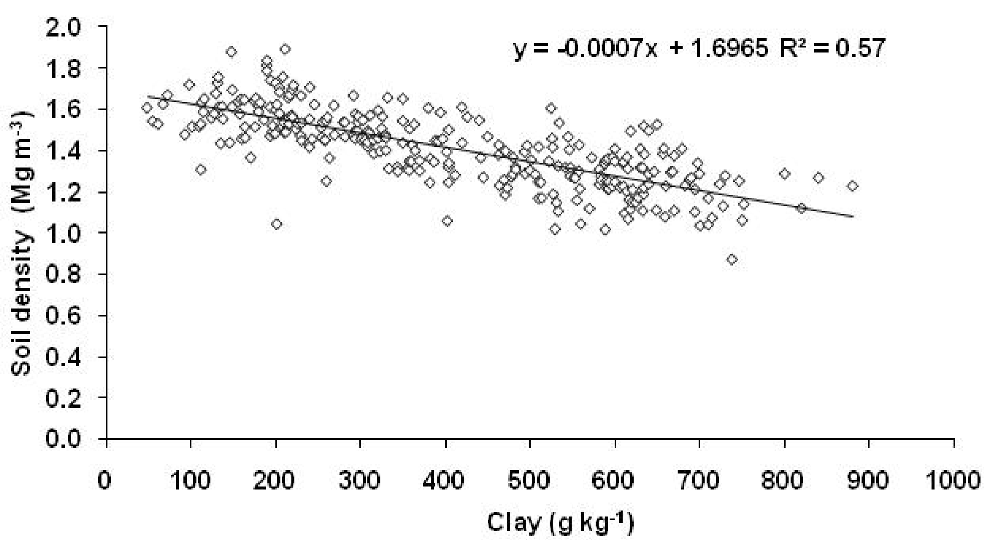

Figure 6 - Soil density as a function of clay in the 292 samples for 25-50 cm in the soils of the Mid-South States.

Table 6 shows the results obtained for soil density as a function of the concentration of clay at the two depths surveyed, i.e. 0-25 cm and 25-50 cm. Figure 7 shows the soil density as a function of the concentration of clay for the two depths surveyed. The overall average for soil density obtained in 292 soil trenches for the depth 0-25 cm is 1.46 Mg m^{-3} and for 25-50 cm is 1.41 Mg m^{-3}.

The correlation found in this study case (Figure 7) is in accordance with that of Reichert; Reinert & Braida (2003). They also found that soil density varies with soil texture: as clay content increases soil density decreases. Sandy soils up to 200 g kg^{-1} clay has a range of soil density between 1.7 a 1.8 Mg m^{-3} while in very clayey soils (more than 600 g kg^{-1} clay) the soil density ranges between 1.2 e 1.3 Mg m^{-3}. This decrease in the density as a function of the clay content shows that clayey soils, because of the nature and size of their particles composition (clay), have natural density lower than sandy soils which have its particles size (sand) larger than clay.

Table 6 – Soil density Mg m^{-3} as a function of clay g kg^{-1} for 0-25 cm and 25-50 cm, in the Mid-South soils cultivated with sugarcane.

Depth	**Clay (g kg^{-1})**							
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**
0-25 cm	1.62	1.56	1.49	1.43	1.37	1.31	1.25	1.18
25-50 cm	1.63	1.56	1.49	1.42	1.35	1.28	1.21	1.14

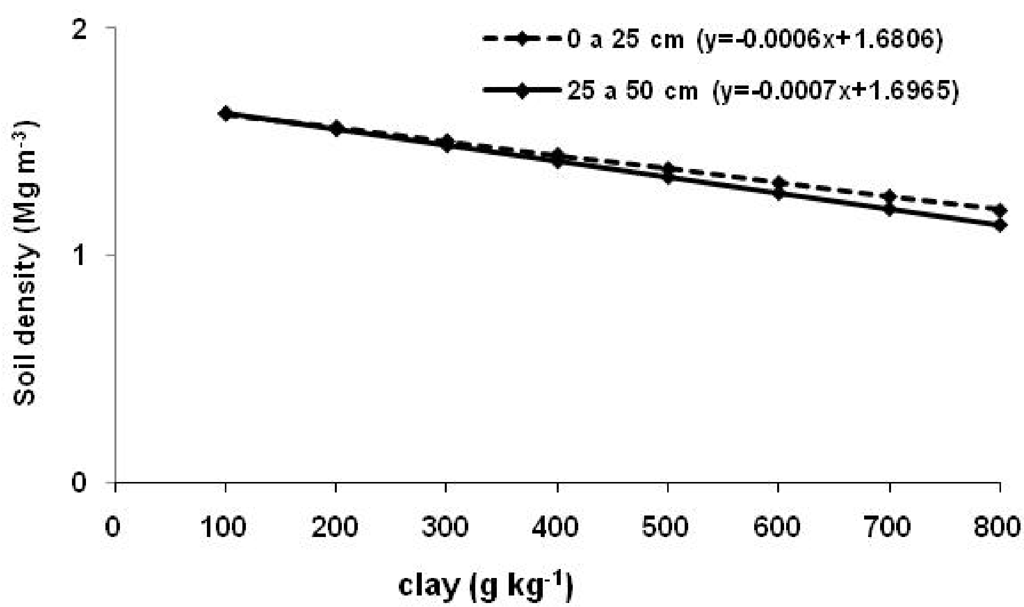

Figure 7 – Soil density as a function of the clay percentage for 0-25 cm and 25-50 cm, in the soils of Mid-South States

Carbon stock in the soil as a function of the clay percentage and soil density

The average density of the soils found in the two layers, jointly with the carbon percentage at the different percentages of clay were used to calculate the quantity of carbon in tons per hectare 0-25 cm, 25-50 cm and for the consolidated depth of 0-50 cm. As was to be expected in the deeper layer (25-50 cm), the quantity of carbon was lower than that in the first layer (0-25 cm) (Table 7 and Figure 8).

Table 7 – Soil carbon stock in Mg C ha^{-1} as a function of the clay g kg^{-1} 0-25 cm, 25-50 cm and 0-50 cm layers in the Mid-South soils with sugarcane.

Depth	**Clay (g kg^{-1})**							
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**
0-25 cm	**29.5**	**35.4**	**40.7**	**45.5**	**49.8**	**53.4**	**56.5**	**59.1**
25-50 cm	**20.2**	**24.4**	**28.2**	**31.6**	**34.5**	**36.9**	**38.8**	**40.3**

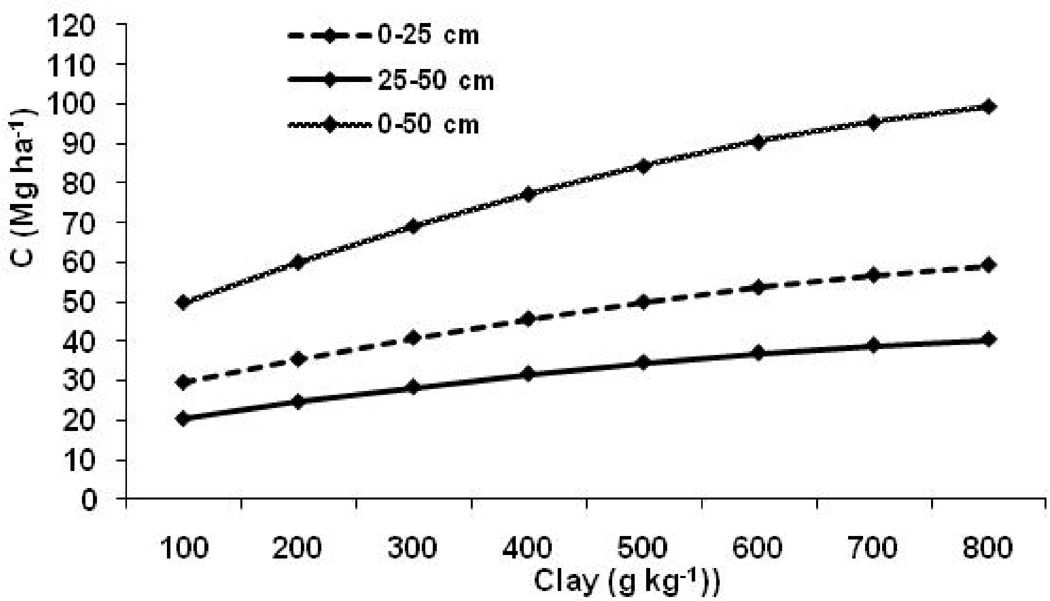

Figure 8 – Soil Carbon in t/ha as a function of the clay percentage of 0-25 cm. 25-50 cm and 0-50 cm layers in the Mid-South soils.

The soil C stocks were computed using the regressions of clay content with C concentration and soil bulk density. Over 93 % of the soil samples had clay contents ranging from 100 to 800 g clay kg soil^{-1}. For this range soil C stocks were estimated to be between 29.5 and 59.1 Mg C ha^{-1} for the 0-25 cm depth interval and 49.7 and 99.4 Mg C ha^{-1} for the 0-50 cm depth interval (Table 7). The mean and median soil C stocks for the whole dataset were 41.6 and 31.8 Mg C ha^{-1}.

The carbon stock has a range of 29.5 Mg C ha^{-1} to 59.1 Mg C ha^{-1} for the depth of 0-25 cm. The lowest value was found in very sandy soils and the highest values on very clayey soils. The same trends were found for the depth of 25-50 cm. with a range for soil carbon stocks from 20.2 t/ha to 40.3 t/ha. The overall values of carbon stock for 0-50 cm depth were 49.7 Mg ha^{-1} to 99.4 Mg ha^{-1}, values compatible with soils under native forest, showing the contribution of a semi perennial crop such as sugarcane for the soil carbon stock (Figure 8); and also denoting the potential of restoration of the carbon stock in sugarcane cultivation soils.

The overall average for carbon stock in the depth of 0-25 cm is 41.61 Mg ha^{-1} and for 25-50 cm is 29.61 Mg ha^{-1}. For the consolidated depth of 0-50 cm the value is 71.22 Mg ha^{-1}. These carbon stock figures were obtained through soil density average of 292 soil trenches and carbon average percentage of 27,552 soil samples.

No survey has been made of the C stocks under these land uses which could be used to evaluate changes in C stocks during the expansion of the area under cane. However, Bernoux et al. (2002) estimated soil C stocks for the entire country to a depth of 30 cm and used data from samples taken in the 1970s (project RADAM) exclusively from areas of native vegetation. The soil under almost the whole area sampled in the CTC cooperative region was classified by Bernoux et al. (2002) as LAC Latossolos and LAC non-Latossols (S2 and S3) and the native vegetation as seasonal semi-deciduous forest (V5) and Savanna (Cerrado – V9). Under the four combinations of soil and vegetation type the estimates of mean and median soil C stocks to 30 cm ranged from 36 to 49 Mg C ha^{-1}, which encompasses the mean and median values estimated for the area under cane in this study.

The values for soil C stocks of the sugarcane area would be expected to be lower than those for the native vegetation as the depth interval was 5 cm less. Using data for 4 or 5 depth intervals to 30 cm from the studies of Sisti et al. (2004) and Jantalia et al. (2007), both on Oxisols (Latossolos) in the south and Cerrado regions, respectively, we estimated for no-till and native vegetation profiles a correction factor for the C stock in this extra 5 cm of soil as 16.0 % (estimated range: 13.6 to 18.4 %). This means that the estimates of mean and median soil C stocks under cane in the Central South region become 48.2 and 36,9 kg C ha^{-1}, values within the range for native vegetation calculated by Bernoux et al. (2002).

In the 1970s most of the area in São Paulo State today planted to sugarcane (60 % of Brazil´s production in this State alone), as well as some other areas in the Central South region, had already been cleared of native vegetation and used for pastures or agriculture. This means that the C content of samples of taken from areas of native vegetation in the 1970s may not represent very accurately the original C content of the soils now under cane, but there seems no doubt that mean soil C stocks under sugar cane are not radically lower than those under native vegetation. . They are actually very close to default values for perennial, not annual, crops, using IPCC Tier 1 data.

CONCLUSION

- A new interval of carbon percentage - between 2 g kg^{-1} and less than 50 g kg^{-1} for the depth of 0-25 cm - can be proposed for tropical soils cultivated with sugarcane.

- The overall average for soil density obtained in 292 soil trenches for the depth 0-25 cm was 1.46 Mg m^{-3} and for 25-50 cm 1.41 Mg m^{-3}.

- The average clay content for 0-25 cm was 325 g kg^{-1} of soil and for 25-50 cm 357 g kg^{-1} of soil.

- The carbon stock showed a range of 29.5 Mg C ha^{-1} to 59.1 Mg C ha^{-1} for the depth of 0-25 cm. The lowest value was found in very sandy soils and the highest values on very clayey soils.

- The same trends were found for the depth of 25-50 cm with a range for soil carbon stocks from 20.2 Mg C ha^{-1} to 40.3 Mg C ha^{-1}.

- The overall average for carbon stock in the depth of 0-25 cm is 41.61 Mg C ha^{-1} and for 25-50 cm is 29.61 Mg C ha^{-1}. For the consolidated depth of 0-50 cm the value is 71.22 Mg C ha^{-1}.

- The overall values of carbon stock for 0-50 cm depth were 49.7 Mg C ha^{-1} to 99.4 Mg C ha^{-1}, values compatible with soils under native forest, showing the benefit of a semi perennial crop such as sugarcane for soil carbon stocks; and also indicates the potential for sugarcane cultivation to restore soil carbon stocks.

BIBLIOGRAPHY

ALBERS, C. N.; BANTA, G. T.; JACOBSEN, O. S.; HANSEN, P. E. Characterization and structural modeling of humic substances in field soil displaying significant differences from previously proposed structures. **European Journal of Soil Science**, Oxford, v. 59. n. 4, p. 693-705, 2008.

BERTOLANI, F. C.; JOAQUIM, A. C.; DONZELLI, J. L. Carta de Solos e Ambientes de Produção Edafoclimáticos. **Revista Stab**, Piracicaba, vol. 27, n. 3, p.26-27, 2009.

BODDEY, R. M.; SOARES, L. H. B.; ALVES, B. J. R.; URQUIAGA, S. Bio-ethanol production in Brazil. In: D. Pimentel (ed.). **Biofuels**. Solar and Wind as Renewable Energy Systems: Benefits and Risks. New York: Springer, 2008. p. 321-356.

BERNOUX, M.; CARVALHO, M. C. S.; VOLKOFF, B.; CERRI, C. C. Brazil's soil carbon stocks. **Soil Sci. Soc. Am. J.** v. 66, p. 888-896, 2002.

CAMARGO, M. N.; KLAMT, E.; KAUFFMAN, J. H. Sistema Brasileiro de Classificação de Solos. **Boletim informativo da Sociedade Brasileira de Ciência do Solo**, Campinas, v. 12, n. 1, p.11-33, jan./abr, 1987.

CAMARGO, O. A.; MONIZ, A. C.; JORGE, J. A.; VALADARES, J. M. A. S. **Métodos de análise química, mineralogical e física de solos do Instituto Agronômico de Campinas**. Campinas: Instituto Agronômico, 1986. 94 p. (Boletim Técnico, 106).

CAMARGO, O. A.; MONIZ, A. C., JORGE, J. A.; VALADARES, J. M. A. S. **Métodos de análise de solos do Instituto Agronômico de Campinas**. Campinas: Instituto Agronômico, 2009. 77 p. (Boletim Técnico, 106, Edição revisada e atualizada)

CANELLAS, L. P.; VELLOSO, A. C. X.; MARCIANO, C. R.; RAMALHO, J. F. G. P.; RUMJANEK V. M.; REZENDE C. E.; SANTOS G. A. Propriedades químicas de um Cambissolo cultivado com cana-de-açúcar com preservação do palhiço e adição de vinhaça por longo tempo. **Revista Brasileira de Ciênca do Solo**, Viçosa, v. 27, p.935-944, 2003.

CONAB 2008. **Acompanhamento da safra Brasileira**: cana-de-açúcar. Companhia Nacional de Abastecimento (CONAB). MAPA. Brasília, 2008.

COPERSUCAR – DIVISÃO AGRONÔMICA. Levantamentos pedológicos. In: **I Seminário de Tecnologia Agronômica**, Piracicaba, 1982. p.163-168.

DONZELLI, J. L.; JOAQUIM, A. C.; BELLINASO, I. F. Sugarcane Production Environments. **Proceedings of ISSCT Congress**, Guatemala, v. 25, p.541-544, 2005.

DONZELLI, J. L.; JOAQUIM, A. C.; BERTOLANI, F. C. Ambientes de produção edafoclimáticos para a cultura da cana-de-açúcar. **Revista Opiniões**, Ribeirão Preto, edição: mar-jun de 2010, p. 20-21, 2010.

EMBRAPA. Centro Nacional de Pesquisa de Solos. **Sistema brasileiro de classificação de solos**. 2 ed. Rio de Janeiro: Ministério da Agricultura e Abastecimento, 2006. 306 p.

FELLER, C.; BEARE M. H. Physical control of soil organic matter dynamics in the tropics. **Geoderma** 79:69-116, 1997.

GALDOS, M.V.; CERRI, C. C.; CERRI, C. E. P.; PAUSTIAN, K.; VAN ANTWERPEN, R. Simulation of Soil Carbon Dynamics under Sugarcane with the CENTURY Model. **Soil Sci. Soc. Am. J.,** v. 73, p. 802-811, 2009.

EGGLESTON, S.; BUENDIA, L., MIWA K.; NGARA, T.; TANABE K. **2006 IPCC Guidelines for National Greenhouse Gas Inventories**. Institute for Global Environmental Strategies. Hayama. Japan, 2006.

JANTALIA, C. P.; RESCK, D. V. S.; ALVES, B. J. R.; URQUIAGA, S.; BODDEY, R. M. Effect of tillage intensity on carbon stocks under a soybean based crop rotation in the Brazilian Cerrado. **Soil Till**. Res. 85, P. 97-109, 2007.

JOAQUIM, A. C.; BELLINASO, I. F.; DONZELLI, J. L.; QUADROS, A. C.; BARATA, M. Q. F; Potencial e manejo de solos cultivado com cana-de-açúcar. In: **VI Seminário Copersucar de Tecnologia Agronômica**, Piracicaba, 1994. P. 1-9.

JOAQUIM, A. C.; DONZELLI, J. L.; QUADROS, A. C.; SARTO, L. F. Potencial de produção de cana-de-açúcar. In: **VII Seminário Copersucar de Tecnologia Agronômica**, Piracicaba, 1997. p. 68-76.

LA SCALA, N. J. R.; BOLONHEZI, D.; PEREIRA, G. T. Short-term soil CO_2 emission after conventional and reduced tillage of a no-till sugar cane area in southern Brazil. **Soil Till. Res.** v. 91, p. 244-248, 2006.

MACEDO, I. C. Greenhouse gas emissions and energy balances in bio-ethanol production and utilization in Brazil. **Biomass Bioenergy**, v. 14, p. 77-81, 1998.

MACEDO, I. C.; SEABRA, J. E. A; SILVA, J. E. A. R. Green house gases emissions in the production and use of ethanol from sugarcane in Brazil: The 2005/2006 averages and a prediction for 2020. **Biomass Bioenergy**, v. 32, p. 582–595, 2008.

MACHADO PINHEIRO, E.F.; LIMA, E.; CEDDIA, M.B.; URQUIAGA,S.; ALVES; B.J.R. & R.M. BODDEY. Impact of pre-harvest burning versus trash conservation on soil carbon and nitrogen stocks on a sugarcane plantation in the Brazilian Atlantic forest region. **Plant Soil**, v. 333, p. 71-80, 2010.

MILLES, N.; MEYER, J. H.; VAN ANTWERPEN. R. Soil organic matter data: what do they mean?. **Proc S Afr Sug Technol Ass**, v. 81, p. 324-332, 2008.

NASSAR, A. M.; RUDORFF, B. F. T.; ANTONIAZZI, L. B.; AGUIAR, D. A.; BACCHI, M. R. P.; ADAMI, M. Prospects of the sugarcane expansion in Brazil: impacts on direct and indirect land use changes. In: ZUURBIER,P.; VOOREN, J. Van. **Sugarcane ethanol**: contributions to climate change mitigation and the environment. The Netherlands: Wageningen Academic Publishers., 2008.

OLIVEIRA, J. B.; MENK, J. R. F.; ROTTA, C. L. Levantamento pedológico semidetalhado dos solos do Estado de São Paulo. **Quadrícula de Campinas:** IBGE, Rio de Janeiro,1979.

OLIVEIRA, J. B.; MENK, J.R.F.; BARBIERI, J. L.; ROTTA, C. L.; TREMOCOLDI, W. A. Levantamento pedológico semidetalhado dos solos do Estado de São Paulo. **Quadrícula de Araras**: Instituto Agronômico, Campinas, 1982. 135 p. (Boletim Técnico, 72).

PARFITT, R. L.; THENG, B. K. G.; WHITTON, J. S.; SHEPHERD, T. G. Effects of clay minerals and land use on organic matter pools. **Geoderma**, Amsterdam, v. 75, n. 1, p. 1-12, 1997.

REICHERT, J. M.; REINERT, D. J.; BRAIDA, J. A. Manejo. Qualidade do solo e sustentabilidade: Condições físicas do solo agrícola. **XXIX Congresso Brasileiro de Ciência do Solo**, Ribeirão Preto, 2003. CD ROM.

SCHIMEL, D. S.; BRASWELL, B. H.; HOLLAND, E. A.; MCKEOWN, R.; OJIMA, D.S.; PAINTER, T.H.; PARTON, W.J.; TOWNSEND, A. R. Climatic. edaphic. and biotic controls over storage and turnover of carbon in soil. **Global Biogeochemical Cycles**, v. 8, p. 279-293, 1994.

SILVER, W. L.; NEFF, J.; MCGRODDY, M.; VELDKAMP, E.; KELLER, M.; COSME. R. Effects of soil texture on belowground carbon and nutrient storage in a lowland Amazonian forest ecosystem. **Ecosystems**, New York, v. 3, p. 193-209, 2000.

SISTI, C. P. J; SANTOS, H. P.; KOCHHANN, R. A.; ALVES, B. J. R.; URQUIAGA, S.; BODDEY, R. M. Change in carbon and nitrogen stocks in soil under 13 years of conventional or zero tillage in southern Brazil. **Soil Till**. Res. 76, p. 39-58, 2004.

SUGAWARA, L. M. S.; RUDORF, B. F. T., VIEIRA, R. M. M. P.; AFONSO, A. G.; AULICINO, T. L. I. N.; CARVALHO, M. A.; MOREIRA, M. A.; DUARTE, V.; SIVA, W.F.; AGUIAR, D. A. **Imagens de satélites na estimativa de área plantada com cana na safra 2005/2006– Região Centro-Sul.** São José dos Campos: INPE (15254-RPQ/815). 2008. 74 p.

SUMAN, A.; SINGH, K. P.; SINGH, P.; YADAV, R. L. Carbon input. loss and storage in subtropical Indian Inceptions under multi-ratooning sugarcane. **Soil and Tillage Research**, Amsterdam, v. 105, n. 2, p. 177-328, 2009.

VALLIS, I.; PARTON, W. J.; KEATING, B. A.; WOOD, A. W. Simulation of the effects of trash and N fertilizer management on soil organic matter levels and yields of sugarcane. **Soil Till. Res.** v. 38, p. 115-132, 1996.