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Riparian forest potential to retain sediment and carbon evaluated by the ^{137}Cs fallout and carbon isotopic ratio techniques

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ABSTRACT

Riparian forests can provide an important service for aquatic ecosystems by sequestering hillslope-derived sediments. However, the width of a riparian buffer zone required to filter sediments is not yet well-understood. Here are used two complementary tracers to measure sediment retention. The ^{137}Cs technique and the soil carbon isotopic ratios (δ^{13}C) are utilized to investigate sediment deposition and erosion rates on a slope transect cultivated with sugarcane followed by a secondary riparian forest zone in Iracemápolis, State of São Paulo, Brazil. The ^{137}Cs technique and the δ^{13}C analysis showed that the width of a riparian vegetation in accordance to a Brazilian Environmental Law (N° 4.771/65) was not sufficient in trapping sediments coming from agricultural lands, but indicated the importance of these forests as a conservation measure at the watershed scale. The complementary δ^{13}C analysis together with soil morphology aspects allowed a better interpretation of the sediment redistribution along the sugarcane and riparian forest transects.

Key words: erosion, δ^{13}C, sugarcane, C_3 and C_4 plants, carbon.

INTRODUCTION

Riparian zones are the ecotons located between aquatic and terrestrial systems, considered as key areas for the stability of the global biodiversity, serving as protection niches for wildlife, and acting as ecological corridor between forest fragments (Kajeyama et al. 2002, Rodrigues and Gandolfi 2001). Besides their ecological function, these "buffer zones" are considered important for waterway protection, being responsible for improving surface water quality. The main mechanisms involved on this function are the filtering and trapping of sediments which result from erosion on upland agricultural fields. These mechanisms are related to changes in surface roughness, water infiltration rates into litter layers, the presence of roots, and the improved structure of soil matrix caused by intense microbiologic activity in the soil (Ampontuah et al. 2006, Izidorio et al. 2005).

A Brazilian Environmental Law (N° 4.771/65) protects these ecosystems by fixing minimum widths of riparian zones to be preserved along the borders of superficial body waters, called as "Legally Protected Areas" (LPA). The importance of riparian zone widths for water resources protection has also been focused by various researchers (Mander et al. 1997, Nilsson et al. 1997). However, isolated studies carried out in Brazil indicate that the widths fixed for LPA are not always wide enough to assure the filter function for nutrients

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(mainly Phosphorus and Nitrogen) and sediments carried from agricultural lands (Sparovek et al. 2001).

Erosion and sediment deposition studies that integrate agricultural systems and riparian forests are essential for the understanding of the functional aspects of complex landscapes, as the watersheds, which contain both elements. This understanding is useful to improve the related environmental legislation and to increase the probability of success on public intervention in restoring riparian systems located in private lands, opening the possibility of a link between environmental and agricultural production programs. Difficulties in carrying such an approach are the choice and confidence on methodologies to predict soil loss and sediment deposition in complex areas. The ^{137}Cs technique aided by the soil carbon isotopic ratio (δ^{13}C) analysis is a sound alternative to investigate the processes involved in such systems.

Caesium-137 is an artificial radionuclide with a half-life of 30.17 years produced by thermonuclear explosions made in the atmosphere and by nuclear reactor accidents. The global fallout of ^{137}Cs began in 1954, with peak values during 1963 and 1964, and decreasing from this maximum to below detection levels since the mid-1980s. ^{137}Cs has been transported to the earth's surface as fallout, which is more abundant in the northern hemisphere than in the southern. Due its relatively long half-time, its strong adsorption on fine soil particles and its low mobility in the soil profile, ^{137}Cs has been used with success as a tracer to make measurements of soil loss and deposition, mainly on the north hemisphere due to its greater abundance (Ritchie and Ritchie 2001, Walling and Quine 1993). Caesium-137 reaches the soil surface by dry deposition and precipitation and it is strongly adsorbed by fine soil particles. Its concentration increases with the increase of the specific surface area of soil particles and its translocation from the surface layer downwards is very slow. Its vertical movement or leaching is a result of soil physical and chemical phenomena and the horizontal movement is related to runoff (He and Walling 1996, Livens and Loveland 1988).

The assessment of ^{137}Cs redistribution is based on a comparison of measured inventories at individual sampling points with an equivalent estimate of the inventory of a representative site of the cumulative fallout input, which was not been subject to soil erosion or deposition. The sampling points with lower inventories than the reference site are taken as locations of soil loss and, therefore, erosion may be inferred. Similarly, sampling points with inventories in excess of the reference level are taken as sediment deposits. Quantitative estimates of erosion and deposition rates from ^{137}Cs measurements are made through conversion models that relate the erosion or deposition rate to the magnitude of the reduction or increase in the ^{137}Cs inventory (Zapata 2003).

The use of the soil carbon isotopic ratio technique in soil research increased in the last years (SIBAE-BASIN 2004), and is based on the differences of the photosynthetic pathways of C_3 and C_4 plants, which cause distinct δ^{13}C values in their tissues (Farquhar et al. 1989). During carbon fixation from the atmosphere, C_3 plants give preference to the lighter C isotopes, resulting more enriched compounds in ^{12}C and consequently lower δ^{13}C values in relation to C_4 plants. These isotopic differences allow the differentiation of the carbon of C_3 and C_4 plants in a simple way (Martinelli et al. 1991, Vitorello et al. 1989). Since sugarcane is a C_4 plant and the riparian forest is composed mainly of C_3 plants it is possible to identify and quantify in the forest soil the contribution of both the carbon derived from the upland sugarcane crop and the carbon derived from the immediate forest (*in situ* carbon).

The main objective of this study is to check the efficiency of a riparian forest in trapping sediments coming from an upland sugarcane field, using the ^{137}Cs technique aided by soil carbon isotopic ratio analysis.

MATERIALS AND METHODS

Characteristics of the Study Area

The selection of the study area was based on the need to find field situations, which present conditions for abrupt changes between soil loss and sediment deposition, in order to allow the analysis of the sensibility of both the ^{137}Cs technique and the soil carbon isotopic ratio analysis in relation to land use changes. Contrasting land uses as agriculture and forestry were considered ideal. Due to difficulties in sampling, counting, and analyses costs, only two aligned transect segments composed by an upper slope portion (800 m) cultivated with sugarcane and a lower slope portion (120 m) covered by a secondary riparian forest were selected in Iracemápolis, State of São Paulo, Brazil (22°35′ S and 47°33′ W). According to Köppen's classification, the climate is of the type Cwa, with an annual mean temperature of 21°C and a mean precipitation of 1,360 mm per year. The mean altitude is 610 m (a.s.l.) and the predominant soil is classified as a Rhodic Hapludox according to Soil Taxonomy (Soil Survey Staff 1993). The main crop of region is sugarcane, which has been continuously cultivated over more than 50 years. Soil samples were taken and analyzed in 2006.

^{137}CS TECHNIQUE

Before Cs analysis, the soil samples were oven dried at 105°C, gently disaggregated, passed through a 2 mm sieve and homogenized. A representative fraction of each sample (an amount of approximately 1.5 kg) was placed into Marinelli beakers for ^{137}Cs activity determination. The ^{137}Cs activities of each 20 cm soil layer expressed in Bq.kg^{-1} were then converted to Bq.m^{-2} taking into account the auger diameter and the soil bulk density. The Cs inventory (Bq.m^{-2}) for each profile was taken as the sum of the activities of the analyzed soil layers.

For the ^{137}Cs determination, points were located on the transect at the following positions: a) five points along the sugarcane transect (ST) segment, spaced 10 m from each other (points –50, –40, –30, –20, –10); and b) twelve points in the riparian forest transect (FT) segment spaced 5 m from each other (points 5 and 10) and 10 m from each other (points from 10 to 110). The transition zone between the ST and FT segments is represented by a 5 m width dusty road. Based on a local inspection of the road cross section, it is assumed that this road did not interfere significantly on the erosion and deposition processes, and also not as a sediment source. For each transect point a composite sample was obtained from five samples collected on contour lines (5 m distant from each other), perpendicularly to the transect. Therefore each composite sample of each soil layer and of each point of the transect represents an average of a 20 m wide down slope land strip.

A HPGE Coaxial Detector (GEM-20180P, PopTop) with an absolute detection efficiency of 0.7% (Wallbrink et al. 2002) for the adopted geometry (1 L Marinelli Beaker) was used for the analysis of samples from the reference site and from the transect points. The above mentioned efficiency was determined experimentally using a standard soil sample with a known Cs activity supplied by the International Atomic Energy Agency (IAEA), Vienna, Austria. Due to the very low ^{137}Cs activity of our soil samples and the very low detection efficiency, the counting time for each sample varied from 24 to 72 hours.

The reference site was chosen in a 20,000 m^2 flat grass land area of an old garden, located at the Campus of São Paulo State University (ESALQ), Piracicaba, SP, Brazil (22°40′ S; 47°38′ W; 580 m a.s.l.), 25 km far from the experimental site. More than 40 years ago the area was embanked in order to establish a very flat grass (*Paspalum notatum* Flugge) field to be used only for recreation. The soil is an embankment with 18% sand, 39% clay, and 43% silt. The climate is very similar to that of Iracemápolis. The reference site being located close to the experimental site was considered adequate as a reference for the fallout deposition in the region. A more complete characterization of the reference site and procedures used for the determination of the reference site inventory can be found in Correchel et al. (2005).

The results of ^{137}Cs loss or gain were calculated by comparison of each inventory point with the reference site inventory according to:

$$\mathrm{Cs_{red}} = \left(\frac{\mathrm{Cs_p} - \mathrm{Cs_{ref}}}{\mathrm{Cs_{ref}}} \right) \tag{1}$$

where $\mathrm{Cs_{red}}$ is the fraction of distributed ^{137}Cs, loss if negative and gain if positive; $\mathrm{Cs_p}$ and $\mathrm{Cs_{ref}}$ are the ^{137}Cs inventories at each sampled point and at the reference site, respectively.

The proportional model (Walling and He 1997) was used to convert the values of $\mathrm{Cs_{red}}$ (%) into soil erosion or deposition rates E (Mg.ha^{-1}.year^{-1}):

$$E = \left(\frac{\mathrm{Cs_{red}}\, \rho_\mathrm{b}\, \mathrm{D}}{\mathrm{TP100}} \right) 10 \tag{2}$$

where ρ_b is the soil bulk density (kg.m^{-3}); D the plowing depth (m); T is the time lapse since fallout occurrence (years); P is a particle size correction factor (taken as unity in the present study because no differences were observed in soil texture along the transects); and the constant 10 adjusts the units. Soil bulk densities were determined dividing the dry soil mass by the correspondent auger hole volume of each 20 cm soil layer. The plough depth was taken as 20 cm depth. The time lapse since fallout peak occurrence and the sampling date was taken as 43 years.

STABLE ISOTOPE (δ^{13}C) TECHNIQUE

Carbon (C) stable isotopes present 6 protons and 6 (^{12}C) or 7 (^{13}C) neutrons in their nuclei. The carbon isotopic composition of a given sample δ^{13}C can be expressed in relative terms by the ratios between the abundance of ^{13}C and ^{12}C (Vitorello et al. 1989):

$$\delta^{13}\text{C‰ (sample)} = \left(\frac{{}^{13}\text{C}/{}^{12}\text{C(sample)}}{{}^{13}\text{C}/{}^{12}\text{C(std)}} - 1\right)1000 \tag{3}$$

where the standard (std) ratio ^{13}C/^{12}C value is that obtained with the international standard Pee Dee Belemnite, and to determine the relative contribution of sugarcane plant C to the forest total soil C, the following equation was used:

$$\text{fc} = \frac{\delta^{13}\text{C}_{\text{OM-SAMPLE}} - \delta^{13}\text{C}_{\text{OM-forest}}}{\delta^{13}\text{C}_{\text{OM-sugarcane}} - \delta^{13}\text{C}_{\text{OM-forest}}} \tag{4}$$

where fc represents the sugarcane C fraction; $\delta^{13}\text{C}_{\text{OM-SAMPLE}}$ is the mean value of δ^{13}C for the organic matter (OM) of samples; and $\delta^{13}\text{C}_{\text{OM-sugarcane}}$ and $\delta^{13}\text{C}_{\text{OM-forest}}$ are the mean values of δ^{13}C for sugarcane (C_4-plant) and the specific forest species (C_3-plants), respectively. The reference δ^{13}C value for the sugarcane OM ($\delta^{13}\text{C}_{\text{OM-sugarcane}}$) determined according to equation 3 was taken as –13.0‰ and for the specific forest species OM as –26.5‰ .

Isotopic determinations of soil samples were made using a Thermo Quest-Finnigan Delta Plus isotope ratio mass spectrometer (Finnigan-MAT – USA) interfaced to an Elemental Analyzer (Carla Erba model 1110 – Italy). Before δ^{13}C analysis, the soil samples were oven dried at 40°C, passed through a 2 mm sieve, ground to a fine powder using a cleaned laboratory mill, and then weighted and loaded into tin capsules. Values of fc according to equation 4 were determined for 24 superficial soil samples (0–5 cm) collected along the FT and ST segments.

SOIL MORPHOLOGY ANALYSIS

Detailed soil morphological descriptions were carried out for the FT segment taking samples from points located at each 10 meters from the upper border of the forest down-slope to the reservoir margin, and at 0–5, 0–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm depth from three pits located at 5, 10, and 20 m from the forest border. The geometrical distribution of the soil horizons and sediments was established using the methodology developed by Boulet et al. (1982). For micromorphological observations and image analysis, thin sections of 5 by 7 cm were prepared from blocks impregnated with a non-saturated polyester resin diluted with styrene monomer. A fluorescent dye allows distinguishing the pores when illuminated with UV light (Cooper et al. 2005). Digital images were acquired from the thin sections and impregnated blocks using a color CCD camera with a resolution of 1024 × 768 pixels (area of 156μm^2.pixel^{-1}). Images were processed using the Noesis Visilog® image analysis software. Particle size distribution was determined by sieving and the Boyoucus method, using a hydrometer, after dispersion with a sodium hydroxide and sodium hexametaphosphate solution (Camargo et al. 1986).

RESULTS AND DISCUSSION

The soil distribution of horizons obtained with the aid of morphological and micro-morphological analysis, the ^{137}Cs inventories, and the soil carbon isotopic ratio within the riparian forest transect segment, are shown in Figure 1.

The soil horizon distribution (Fig. 1A) is characterized by presenting a layer of sediments covering the original soil that thins gradually down-slope, although the thinning of the sediment layer is not homogeneous, but dependent of the slope shape. Depressions at the soil surface or changes in the micro-relief steepness are associated with thicker layers of sediment deposition as shown by Boulet et al. (1982). The analysis of pore morphology indicates a great contrast between the sediment layers and the original soil. Probably during the deposition process, the soil particles carried by the water were deposited and densely packed favoring the formation of micropores in detriment of macropores. The sediment layers in this case can be easily distinguished by field

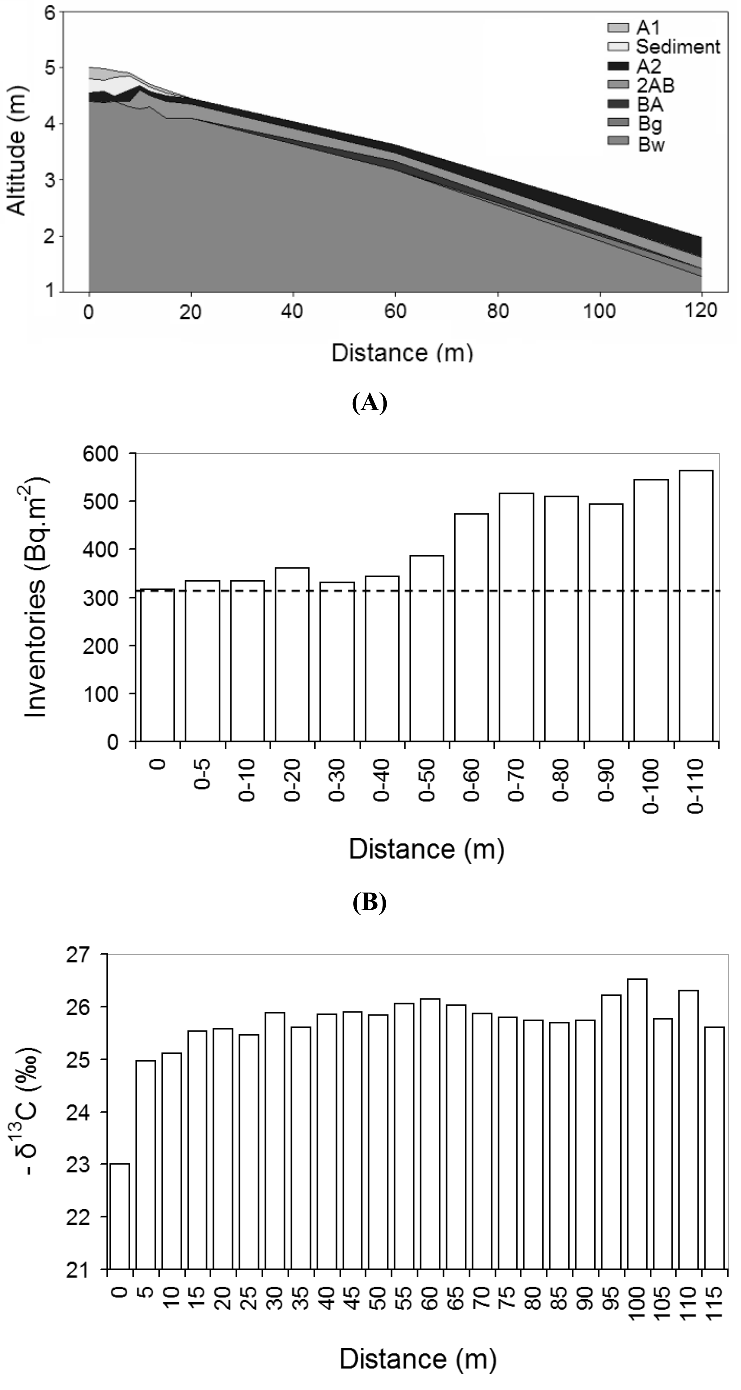

Fig. 1 – (A) Bi-dimensional soil horizon distribution within the forest transect (FT) segment determined with the aid of morphological and micro-morphological analyses. The terms A1, A2, 2AB, BA, Bg, and Bw represent designations for horizons and other soil layers. (B) ^{137}Cs inventories of the points along the FT segment. The dot line represents the inventory value at the reference site. (C) Values of δ^{13}C of the points along the FT segment.

morphology description and their main difference in relation to the original soil is the aggregation and porosity (Cooper et al. 2005, Boulet et al. 1982).

A qualitative analysis of the inventories of both transect segments allows to note that most of the sugarcane points were eroded profiles (^{137}Cs inventories less than the reference) and all the riparian forest points were profiles of sediment deposition (^{137}Cs inventories higher than the reference). Figure 2 presents the estimated erosion (+) and sediment deposition rates (–) determined by the ^{137}Cs technique along the ST and FT segments.

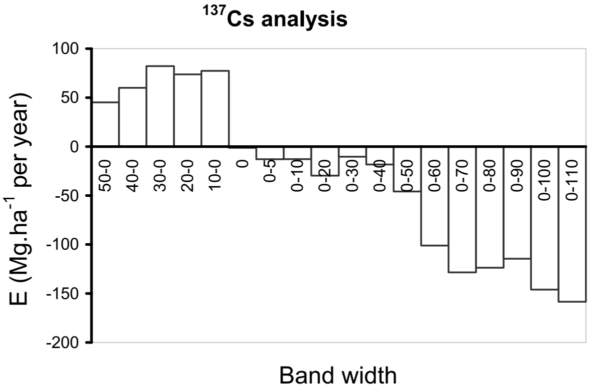

Fig. 2 – Average soil erosion (E) (+) and deposition (D) (–) rates as a function of band widths (ST – sugarcane and FT – riparian forest segments) obtained using the ^{137}Cs technique.

A significant increase of ^{137}Cs inventories was observed along the FT segment down to the last sampled point which is 110 m distant from the upper edge the forest (Fig. 1B). However, the quantification of sediment redistribution inside the FT segment is not as simple as in cultivated soils where the ^{137}Cs fallout inputs can be assumed to be uniformly mixed within the cultivation layer. The increase in the inventories along the forest transect could be attributed to a selective redistribution of fine sediment as well as due to the exponential decline of ^{137}Cs concentrations with depth in the original undisturbed soil profile of the forest. Samples taken from the upper 5 cm soil profile of the FT segment down to 80 m did not show important textural differences or trends that could explain the selective transport of fine sediments along the transect. Due to the exponential decline of the ^{137}Cs concentrations with depth in the original undisturbed soil profile of the forest, the gain of a given amount of ^{137}Cs in relation to the reference inventory would correspond to a lower deposition rate if compared to a same ^{137}Cs gain in a cultivated soil. For undisturbed soils alternative approaches are then required to derive erosion and deposition rates like empirical or other theoretical models based on the ^{137}Cs distribution in soil profiles (Wallbrink et al. 2002). However, in the present study, the riparian forest is adjacent to an upland sugarcane crop which is clearly the source of the sediment deposited in the forest. Besides the sediments coming from the upland field some small amount could also be deposited just in the lower strip edge of the forest situated 50 m distant from the last sampling point of the FT segment. However, the lower forest border contour level is in a much higher level than the drainage ditch of a large downstream water reservoir borderlined by the forest. Therefore, considering that the forest would be trapping most part of the sediment delivered by the upland sugarcane crop, it is reasonable to consider that the deposition rate occurred in the forest is of the same order of magnitude of the upland sugarcane sediment delivery rate.

The ^{137}Cs technique was sensitive to the presence of the riparian forest (Fig. 2). The technique indicates a predominant occurrence of erosion process in the ST segment (inventories lower than the reference site) and sediment deposition in the FT segment (inventories higher than the reference site). The magnitude of the sediment deposition rate in the FT segment was than calculated using equation 2.

According to Correchel et al. (2005), the inventories at the reference site varied from 277 to 367 Bq.m^{-2}, resulting an average reference value of 314 ± 34 Bq.m^{-2}. The ^{137}Cs activities decreased in depth from 302 Bq.m^{-2} for the upper 15 cm of the soil profile to 11 Bq.m^{-2} for the 15-25 cm layer. No significant ^{137}Cs activity was detected below this layer. The randomic spatial variability of the data of the reference site presented a CV of 11%.

The band widths were obtained taking average values of soil erosion or sediment deposition rates (E) for each band. For example, the width bands 30–0 m and 0–40 m represent average of three erosion rates and six sediment deposition rates, respectively, taken from –30 to 0 m and from 0 to 40 m of distance. The average of the thirteen ^{137}Cs inventories of the FT segment was 564 Bq.m^{-2} and the correspondent estimated sediment deposition rate was –158 Mg.ha^{-1}.yr^{-1}. Using the same proportional model, the erosion rates estimated for the five upland sugarcane points of the same transect are of the order of 45 Mg.ha^{-1}.yr^{-1}. The comparison of the sediment deposition rate in the FT segment with the erosion rate in the sugarcane crop shows clearly the important effect of the riparian forest system in the control of the out of farm sediment delivery. This result also indicates that the riparian forest length adopted the Brazilian Environmental Law ($\approx$ 30 m) is not sufficient to retain the sediment transported by the runoff confirming the results obtained by Sparovek et al. (2001).

δ^{13}C values (Fig. 1C) determined inside the FT segment indicate that the amount of sugarcane carbon in relation to the total soil carbon in the upper 5 cm layer decreases with distance. This result of the sugarcane carbon concentration in the FT segment is in agreement with the soil morphology analysis. Therefore, δ^{13}C data show that the higher sediment deposition occurs at the beginning of the FT segment, while ^{137}Cs inventories present an opposite behavior. The contribution of sugarcane carbon to the total soil carbon of the surface riparian forest soil (upper 5 cm layer) is shown in Figure 3.

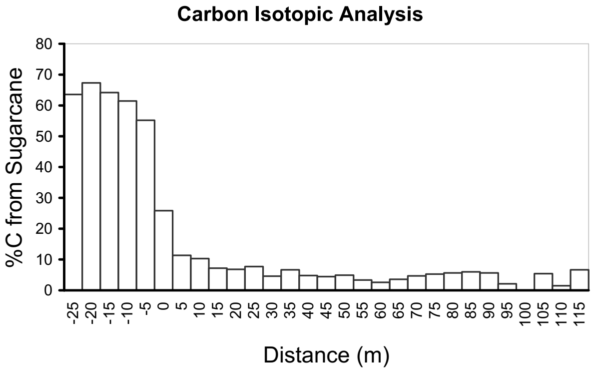

Fig. 3 – Contribution of the sugarcane carbon (%SC) to the total soil carbon in the sugarcane transect (ST) segment and in the riparian forest transect (FT) segment.

The percentage of sugarcane carbon contribution (%SC) to the total soil carbon in the upper 5 cm layer is high in the ST segment, as expected, and there is a tendency of a decrease in this %SC along the FT segment, also as expected. The main sources of carbon in the sugarcane crop field soil result from the practice of burning the sugarcane leaves and trash before harvest, and the decomposition of remaining leaves and other residues after harvest. It can be observed in Figure 3 that the amount of sugarcane carbon in the sugarcane transect segment (from –25 to –5 m distance) only ranges from 55.2 to 67.3%. These values of %SC in the sugarcane area are not closer to 100% as expected because the organic matter of the soil in the ST segment represents a mixture of sugarcane and native forest residues. The introduction of the sugarcane crop in the ST segment was made in a region of native forest about 50 years ago and the residues of this native forest are still present. Similar results were reported by Vitorello et al. (1989).

Fifteen meters inside the FT segment the amount of sugarcane carbon found in the total soil carbon practically oscillates around an average of 4.7%. The experimental data of %SC were adjusted using the following equation

$$\%\mathrm{C} = \left\{ \frac{[100.9 - 7.8]}{[1 + \exp((\mathrm{x} - 1.3)/2.5)]} \right\} + 7.8(\mathrm{r}^2 = 0.99).$$

Through this sigmoid mathematical adjustment it was possible to confirm that after about 15 m inside the FT segment the amount of sugarcane carbon found in the total soil carbon practically trends to a constant value. One of the sources of the sugarcane carbon present in the soil of the FT segment is the runoff, which transports both soil suspended sediments and carbon from the upland sugarcane field. This decrease in the sugarcane carbon concentration in the FT segment as discussed above is in agreement with the soil morphology analysis, which could not be clearly understood only in light of the ^{137}Cs redistribution analysis.

The ST segment presented the heaviest δ^{13}C values, varying from –18.2 to –17.4‰, with an average of –17.8 ± 0.3‰ (n = 4). Such low isotopic values are in the range typically found for C_4 plants. The highest δ^{13}C values, varying from –26.5 to –23.0‰, with an average of –25.7 ± 0.7‰ (n = 24) were found for the FT segment. Typically δ^{13}C for C_3 plants fall between –25 and –34‰, and the most common values vary from –26 and –29‰ (Boutton 1991, O'Leary 1988).

CONCLUSIONS

The results obtained by the ^{137}Cs technique and soil carbon isotopic ratio analysis indicated the efficiency of riparian vegetation in trapping sediments coming from agricultural lands and its importance as a conservation measure at the watershed scale.

The results allow stating that the minimum forest width of 30 m would not be enough to assure the sediment trapping function of the riparian vegetation for the local conditions of soil, climate, land use, topography, and the kind of riparian vegetation, contradicting the Brazilian Environmental Law (Law 4.771/65) if adopted for such conditions.

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RESUMO

As matas ciliares podem fornecer serviços importantes para os ecossistemas aquáticos sequestrando sedimentos oriundos das áreas de encostas. No entanto, a largura da zona ripária necessária para a retenção de sedimentos ainda não está bem determinada. Aqui são usadas duas técnicas complementares para medir a retenção de sedimentos. As metodologias do ^{137}Cs e da composição isotópica do carbono (δ^{13}C) são utilizadas para avaliar a deposição de sedimentos e taxas de erosão em uma encosta cultivada com cana-de-açúcar seguida por uma mata ciliar situada em Iracemápolis, no Estado de São Paulo, Brasil. As análises pelas técnicas do ^{137}Cs e δ^{13}C mostraram que a largura da mata ciliar definida pela Lei Ambiental Brasileira (N° 4.771/65) não foi suficiente na retenção de sedimentos oriundos de áreas cultivadas, mas indicou a importância destas florestas como medida de conservação de bacias hidrográficas. A análise complementar de δ^{13}C junto com informações morfológicas do solo permitiu melhor interpretação da redistribuição de sedimentos ao longo das áreas de cana-de-açúcar e mata ciliar.

Palavras-chave: erosão, δ^{13}C, cana-de-açúcar, plantas C_3 e C_4, carbono.

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