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Sediment deposition in riparian ecosystems evaluated by different methods

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Abstract Riparian forests play an important role in water conservation. These ecosystems filter and trap sediment produced by erosion and prevent this reaching the waterways. In Brazil, laws protect riparian forests. The established legal widths are determined empirically, based on the width of waterways, with no clear scientific basis. This paper combines three methodological approaches (^{137}Cs, WEPP and soil morphology) to study the effect of a riparian forest in trapping sediment mobilized from upslope sugarcane fields. The study area is located in the south of Brazil. The results will help support Brazilian legislation, by providing a better understanding of the functions of riparian forests in relation to water quality. A good correlation was found between the results provided by the three methodologies. All showed that most of the sediment deposition occurs in the first few metres of the riparian forest and decreases towards its interior. Estimates of soil loss provided by ^{137}Cs and WEPP were similar. The morphology of the sediment and the ^{137}Cs distribution in the profile suggests that deposition occurred during an extreme storm and probably a single erosion event.

Key words caesium-137; erosion model; riparian forests; sedimentation; sediment trapping; soil morphology

INTRODUCTION

Riparian ecosystems are ecotones located between the aquatic and terrestrial systems and are important for recharging waterways and for improving water quality. The key mechanisms involved are the filtering and trapping of sediment that is mobilized by erosion in the watershed. Biologically, they are considered key areas for the stability of global biodiversity, they serve as protection niches for wildlife, and they act as ecological corridors between forest fragments (Rodrigues & Gandolfi, 1998, 2001). Riparian areas are protected by the Brazilian environmental legislation that prescribes a strip of land bordering the river system that must be preserved. The width of the strip is linked to the size of the river, but a clear scientific basis for ensuring benefits in terms of water quality or the biological status of the watershed is lacking (Lima & Zakia, 2001; Rodrigues & Gandolfi, 2001).

Erosion and sediment deposition studies that integrate the agricultural systems (the main sediment sources) with riparian forests (the sediment traps of environmental law) are essential for understanding the functional aspects of complex landscapes containing both elements. This understanding may be useful for refining the related environmental legislation and for increasing the effectiveness of public intervention in restoring the riparian systems. We can identify three methodological approaches capable of such integration: (a) the ^{137}Cs technique of direct erosion and sedimentation assessment (e.g. Walling & Quine, 1993), (b) process-based erosion models (e.g. Sparovek *et al.*, 2001), and (c) soil morphological and micro-morphological studies supported by inventories of soil properties (Castro *et al.*, 2003).

Walling & Quine (1993) provide a useful discussion of the application of radiotracers for erosion and sedimentation assessment. Over the past 50 years much research has been undertaken to develop an improved understanding of the movement and fate of ^{137}Cs in the environment. Scientists from different countries have shown that measurements of the spatial pattern of ^{137}Cs inventories can be used quickly and efficiently to derive estimates of rates of soil loss and deposition on the landscape (Ritchie & Ritchie, 2001). The assessment of ^{137}Cs redistribution is commonly based on a comparison of measured inventories at individual sampling points with an equivalent estimate of the inventory for an undisturbed, uneroded site representative of the cumulative fallout input. The sampling points with lower inventories than the reference are seen to represent points where there has been loss of radiocaesium-labelled soil and, therefore, where the occurrence of erosion may be inferred. Similarly, sampling points where the inventories are in excess of the reference level are considered to represent points where Cs-labelled sediment has been deposited. Quantitative estimates of erosion and deposition rates from ^{137}Cs measurements are made using calibration procedures or conversion models that relate the erosion or deposition rate to the magnitude of the reduction or increase in the ^{137}Cs inventory (Zapata *et al.*, 2002).

The development of quantitative water erosion models has been in progress since the 1950s. The initial approaches used for soil loss assessment, based on statistical relationships between rainfall and runoff parameters (driving force) and soil, crop management and erosion control practices (resistance) were refined in more recent years to produce process-based models (e.g. Nearing *et al.*, 2001). These models have the advantage of being applicable in conditions where no long-term statistical relationships are available and in studies that also consider soil deposition and sediment enrichment processes (i.e. not only soil loss as in the first models). Based on existing experience and the data available for modelling, the Water Erosion Prediction Project (WEPP) (Flanangan & Nearing, 1995) was employed for process-based erosion assessment in this study.

Soil morphological studies, when carried out in detail over extensive areas, can go beyond the objective of soil profile classification. Working in French Guiana, Boulet *et al.* (1982) developed a methodology by which the lateral bi-dimensional configuration of the soil horizons along a transect was represented. These authors used this methodology to explain soil evolution along different transects and the pedogenetic processes that led to their formation. In sedimentation studies, this approach, coupled with micromorphological and particle size distribution analysis, can be used to describe the geometry and the morphology of the sediment within the landscape.

The objective of this study was to combine these three methodological approaches (^{137}Cs, WEPP and soil morphology), whilst at the same time carrying out independent assessments for the same area (transect). In this context, the effect of a riparian forest in trapping sediments mobilized from the upslope sugarcane fields is compared internally (between methods) and with a control transect of similar characteristics, but without the forest. Support for Brazilian legislation through the provision of a better understanding of the functioning of riparian forests functions in relation to water quality, and the design of reliable tools for quantitative sedimentation assessment are further developments that can be expected from this research.

MATERIALS AND METHODS

The study area is located in Iracemápolis, SP, Brazil, 22°35′S, 47°33′W. The annual mean temperature is 21°C, with a mean annual precipitation of 1360 mm year^{-1}. Regionally, the mean altitude is approximately 610 m (m.a.s.l.) and the predominant soil is a Rhodic Hapludox (Soil Survey Staff, 1992). The main crop is sugarcane, which has been continuously cultivated since before 1962. Two transects of similar length and slope were established. The Forest Transect (FT) is composed of an upper slope cultivated with sugarcane and the lower slope is covered by secondary forest (from the edge of the sugarcane to the river system). The Sugarcane Transect (ST) is totally cultivated with sugarcane, up to the river margin.

Soil samples for measurement of the ^{137}Cs inventory were collected from seven points on transect FT and seven points on transect ST, as shown in Fig. 1. The distance between both parallel transects was 300 m and they were located in similar topographic situations (slope shape, steepness, and length). The soil samples for ^{137}Cs determination collected at each position comprised composite samples collected from five points (5 m apart) in a line perpendicular to the main transect. Bulk samples were collected from depths of 0–20 cm, 20–40 cm and 40–60 cm using a 6.0 cm diameter cylindrical hand auger. Pits were excavated on transect FT, at 5 and 10 m from the forest border. These were used to collect depth-incremental samples down to 60 cm in the soil profile in increments of 5 cm. Gamma-ray analyses were made using an EGG & ORTEC spectroscopy system, comprising a high purity coaxial germanium detector GEM 20-180p, providing a detection efficiency of 0.7% when using a 1-litre Marinelli beaker. The counting time for each sample varied from 24 to 72 hours according to sample activity

Erosion modelling using WEPP was undertaken using a GIS interface described by Ranieri *et al.* (2002), the procedure for estimating sediment deposition rates in riparian forest reported by Sparovek *et al*. (2001) and input parameters adapted from the methods indicated in Sparovek & Schnug (2001). Basic WEPP soil input parameters were obtained from soil analysis, but hydraulic conductivity was adjusted to field measured values. Detailed soil morphological descriptions were made in two pits on the FT, considering the first portion of the forest (Fig. 1). 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 cm × 7 cm were prepared from impregnated blocks. Undisturbed and oriented samples were impregnated with a non-saturated polyester resin diluted with styrene monomer. A fluorescent dye distinguished the pores when illuminated with UV light (Murphy, 1986). Digital images were acquired from the thin sections and impregnated blocks using a colour CCD camera with a resolution of 1024 × 768 pixels (area of 156 μm^2 $pixel^{-1}$). Images were processed using the Noesis Visilog® image analysis software. Total porosity (tap) was calculated as the sum of the areas of all the pores divided by the total area of the field, expressed as a percentage. The pores were divided into three shape groups, i.e. rounded, elongated and irregular, using two indexes and thresholds defined in Table 1:

$$I_1 = \frac{P^2}{(4\pi A)} \tag{1}$$

where P is the perimeter of the poroid and A its area, and:

$$I_2 = \frac{\frac{1}{m}\sum_i (N_I)_i}{\frac{1}{n}\sum_j (D_F)_j} \tag{2}$$

where N_I is the number of intercepts of an object in the direction i (i = 0°, 45°, 90° and 135°), D_F is the Feret diameter of an object in the direction j (j = 0° and 90°), m is number of i directions and n is the number of j directions.

Table 1 Definition of the shape classes of the poroids.

Pores	Shape indexes	
	I_1	I_2
Rounded (Roun)	$I_1 \leq 5$	
Elongated (Elon)	$5 < I_1 \leq 25$	≤ 2.2
Irregular (Irr)	$5 < I_1 \leq 25$ or > 25	> 2.2

RESULTS AND DISCUSSION

Figure 1 summarizes the main results obtained from the three methods for the forest transect. A reference ^{137}Cs inventory obtained from an area located 20 km from the study site provided an average value of 314 ± 34 Bq m^{-2} (Correchel *et al.*, 2003). Based on this reference value, it was possible to observe that all FT points are deposition points. A significant increase in ^{137}Cs inventories along the riparian forest transect down to the last sampled point (60 m distant from the forest upper edge) was observed. The ^{137}Cs distribution in the profile (P1) showed the presence of a deep layer (35–40 cm) of sediment deposited over the original forest soil profile, which is also labelled c. In the second profile, (P2), the ^{137}Cs distribution did not show the presence of a sediment layer and the measured total inventory (217 Bq m^{-2}) was lower than that for the first profile (P1) and the reference inventory. The quantification of sediment redistribution within the riparian forest transect is not as simple as for cultivated soils, considering that the ^{137}Cs fallout inputs cannot be assumed to be uniformly mixed within the upper soil layer. The increase in the inventories along the forest transect can be attributed to selective redistribution of fine sediment or to the exponential decline of ^{137}Cs concentrations with depth in the original undisturbed soil profile of the forest. Therefore, the addition of a given amount of ^{137}Cs, in relation to the reference inventory, would correspond to a lower deposition rate than for the same increase in

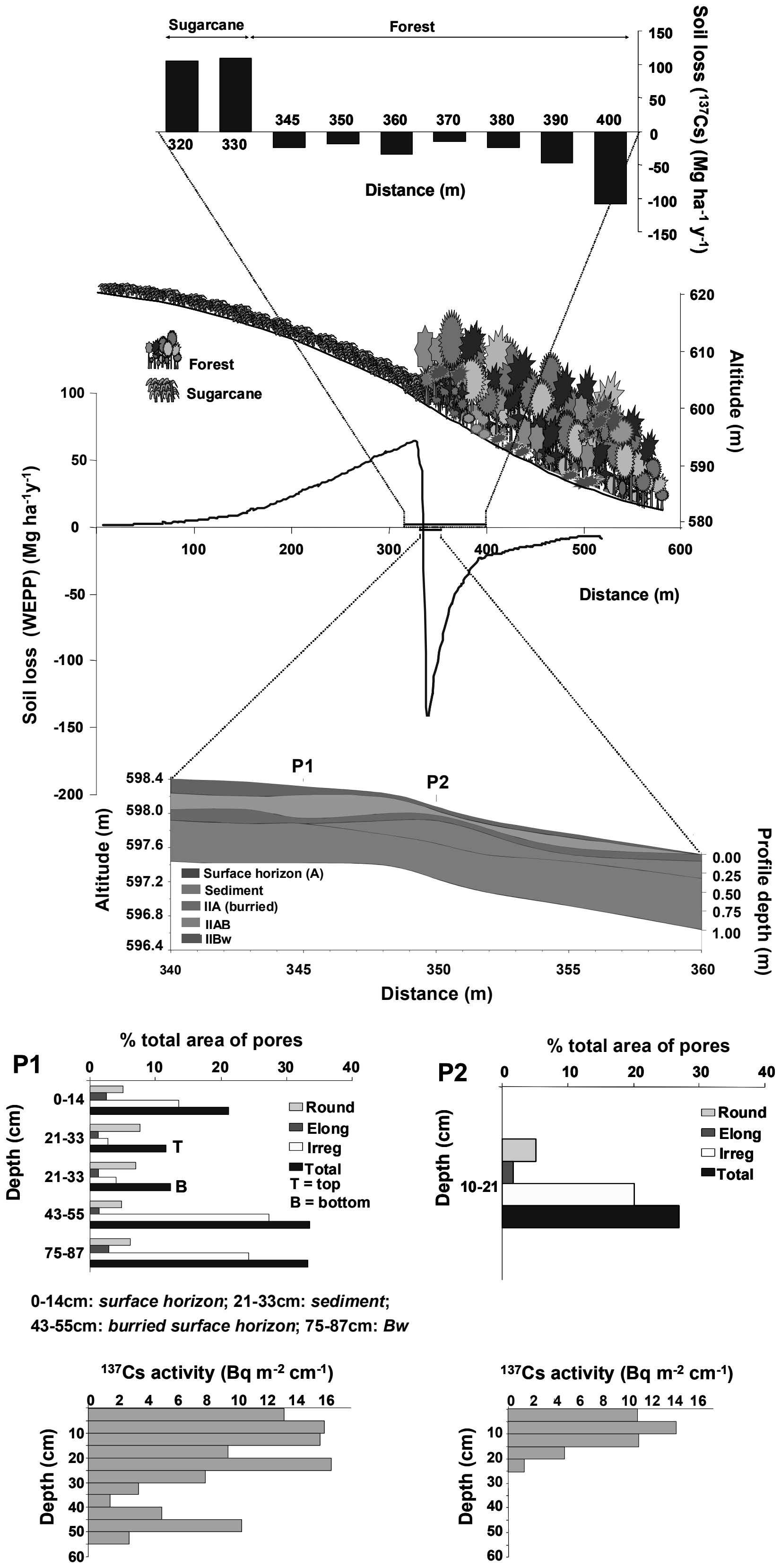

Fig. 1 Site location and topographical profile, erosion rates (^{137}Cs, WEPP), soil morphological description (horizons and pore distribution) in Iracemápolis (Forest Transect), Brazil.

the ^{137}Cs inventory for a cultivated soil. For undisturbed soils, alternative approaches are required for deriving erosion and deposition rates, such as empirical and other theoretical models based on the ^{137}Cs depth distribution in the soil profile. However, in the present study, the riparian forest is adjacent to upslope sugarcane fields, which are the exclusive source of the sediment deposited in the forest. Considering that the forest would be trapping most of the sediment delivered from the sugarcane fields, it is reasonable to consider that the deposition rate in the forest is of the same order of magnitude as the sediment delivery rate. The magnitude of the sediment deposition rate in the FT was calculated using the proportional model (Mitchell *et al.*, 1980; De Jong *et al.*, 1982), applied to a sugarcane crop soil profile, but using the average of the inventories along the forest transect as the ^{137}Cs inventory.

The average ^{137}Cs inventory in the first 60 m forest transect was 484 Bq m^{-2} with a corresponding sediment deposition rate of 108 Mg ha^{-1} year^{-1}. Using the same proportional model, the erosion rates estimated for the two upslope sugarcane points on the same transect are of the order of 100 Mg ha^{-1} year^{-1}. Figure 2 shows the erosion rates estimated by ^{137}Cs and WEPP for the sugarcane transect (ST). Based on the average inventory of the (ST), the estimated erosion rate for this area was 34 Mg ha^{-1} year^{-1}. The magnitude of both estimates are similar, except for the first transect point. This point is located very close to a dirt road, so probably mechanical soil distribution for road building and maintenance can be expected in this position. Intense mechanical soil movement associated with sugarcane fields was also described by Sparovek *et al.* (2000).

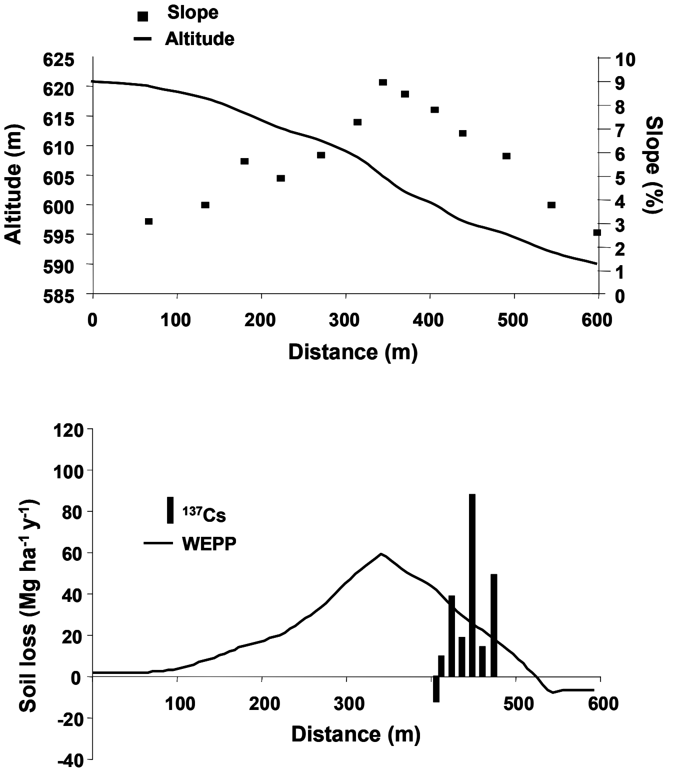

Fig. 2 Topographical profile, slope values and erosion rates (^{137}Cs, WEPP) in Iracemápolis (Sugarcane Transect), Brazil.

Erosion estimation using WEPP and the data collected in the field was sensitive to the presence of the riparian forest (Fig. 1). Erosion ceased abruptly and was replaced by deposition at the edge of the forest, immediately after the border with the sugarcane. Using the assumptions of the model, the increased surface roughness produced by the forest's litter layer and the higher infiltration rate of the forest soil (double that of the sugarcane soil) reduces runoff velocity and volume. The lower available kinetic energy and runoff volume result in a lower sediment carrying capacity and detachment rate, resulting in the immediate deposition of part of the transported sediment, starting with the coarser fractions (stable aggregates and sand). Sedimentation will continue inside the forest, with the rate decreasing with distance into the forest. The magnitude of this process is comparable to the results provided by the ^{137}Cs measurements (peak values) and the shape of the deposition profile is consistent with the soil morphological field descriptions.

The bi-dimensional distribution of the soil horizons and sediments is shown in Fig. 1. The soil horizon distribution within the forest is characterized by presenting a layer of sediment that covers the original soil and thins gradually down slope. The thinning of the layer of sediment is not homogeneous; it depends on the form of the landscape and on the depressions found at the soil surface. Depressions at the soil surface or changes in the steepness of the micro-relief are associated with thicker layers of sediment deposition. The opposite situation is found in non-depressions and steeper areas inside the riparian area. This evidence is consistent with the ^{137}Cs distribution in the soil profiles (P1 and P2, Fig. 1). Consequently, sediment deposition resulted in a smoother landscape in the first few meters of the riparian area. Although the detailed morphological studies showed the presence of sediment layers, no clear particle size selectivity was observed between the sediment and the original soil, probably because of the high clay content of the entire soil profile.

The pore size distribution of the first profile (P1) and the sediment layer in profile 2 (P2) are represented in Fig. 1. Irregular pores dominate in all the horizons, with the exception of the sediment layers in P1. In the sediment layers, where a blocky to massive structure dominates, these irregular pores practically disappear. In these layers the dominant pores are the rounded pores of medium and small size. Differences in the total area of pores were also evident between the soil and the sediment layer (Fig. 1). In P1 and P2, the sediment at the surface is characterized by a higher porosity and more irregular pores. This can be explained by the fact that intense biological activity and contraction and expansion processes influence this layer. The analysis of the pore morphology shows a great contrast between the sediment layers and the rest of the soil. Probably during the deposition process the soil particles carried by the water are deposited and densely packed, favouring the formation of micropores to the detriment of the macropores. The sediment layers in this case can be easily distinguished by field morphology description and the contrasts with the soil on which it was deposited are due mainly to aggregation and porosity formation processes.

Although the three methods provided a similar and complementary picture of the erosion and sedimentation processes in the riparian system, one difference was clear. The ^{137}Cs inventory from the bulk samples (collected in 5-m transects perpendicular to the principal slope line) did not show the extreme deposition at the forest edge that was evident in the ^{137}Cs inventory for the first soil profile, in the soil morphological descriptions and the WEPP modelling. The most probable reason for this is the lateral variability, which is not detected by the other methods that consider only the main slope line. The extreme deposition caused by the abrupt change in soil and superficial conditions moving from sugarcane into the forest are affected by micro-topographical conditions (e.g. impoundments, small convex elevations, channels) that were considered only in the bulk sampling procedure, thus affecting its results. Extension of the analysis to a bi-dimensional design for all methods may confirm this hypothesis and generate a better understanding of the small scale spatial variability of sediment trapping in riparian systems. Also, the combination of the three methodological approaches provided a more comprehensive interpretation of the results. The evidence that the majority of the sediment was deposited as a result of a few (or a single) extreme events, a trend also observed in other environmental conditions (Edwards & Owens, 1991; Douglas *et al*., 1999; White & Garcia-Ruiz, 1998, Larson *et al*., 1997), resulted from a combined analysis of the three methods. The buried surface horizon, lying beneath the deposited sediment that was observed in the field morphological studies was labelled with ^{137}Cs, and was thus recent (formed after 1962). In 1962 sugarcane and the riparian forest had been established in the area for several years. A new surface horizon, also labelled, with morphological features and pore size evidencing soil structure intensively affected by biological process is overlying consolidated and randomly deposited sediment. This suite of evidence negates a continuous and gradual deposition (no laminar structures and abrupt instead of gradual transition from both the buried and the current surface horizons) and suggests a single major deposition event occurring after fallout. The effectiveness of the riparian system in retaining large amounts of sediment from extreme storms is another important aspect, related to water quality and environmental assessment of soil conservation that can be evaluated by the combined methodological approach suggested in this study.

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