Using ^{137}Cs measurements and sediment yield monitoring to document catchment-scale sediment dynamics and budgets

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Abstract The rapid expansion of agriculture in Brazil has increased erosion rates and sediment yields, causing many negative environmental and economic impacts. Given the need to reduce the negative impacts, there is an important need for studies that assess the response of catchment sediment dynamics and budgets to soil and water conservation practices. ^{137}Cs measurements have been combined with measurements of sediment yield, to study the sediment dynamics and budget of a small (1.19 km^2) rural catchment in southern Brazil. ^{137}Cs measurements have been used to estimate medium-term erosion and deposition rates along 17 transects in tobacco growing areas. These data have been used to estimate sediment mobilization rates from the cultivated areas subject to significant erosion. By combining the information on sediment mobilization and deposition rates provided by the ^{137}Cs measurements with available measurements of sediment yield, a sediment budget for the catchment has been established.

Key words soil erosion, sediment yield, tobacco cultivation, Brazil, catchment management, caesium-137

INTRODUCTION

In recent years, the international scientific community has devoted considerable effort to quantifying the on- and off-site impacts of conservation agriculture on natural resources (Valentin *et al.*, 2008; Minella *et al.*, 2008; Nyssen *et al.*, 2009; Verbist *et al.*, 2010). In this context, catchment sediment yield has been used as a key indicator, since an important feature of conservation agriculture is soil erosion control (Leys *et al.*, 2010). However, the complexity of the processes linking the catchment surface to the river channels, and scale effects, introduce important problems into the use of measurements at a catchment outlet to deduce the erosion and sediment delivery dynamics of the upstream area (Jetten & de Vente, 2011). There is a need to couple such measurements with information on catchment-scale sediment redistribution and transfer. Such information will not only contribute to an improved understanding of erosion and sediment delivery processes and the efficacy of soil conservation practices, but it also can be used for calibration/validation of spatially distributed models (Hessel *et al.*, 2003).

A strategy focusing on the integrated assessment of the catchment's sediment budget (Walling & Collins, 2000) provides a valuable approach for assembling information on the mobilization and transfer of sediment within a catchment and linking this to the sediment yield measured at the basin outlet. This approach involves the integration of several different techniques/methodologies that together provide information on sediment mobilization, redistribution, transport, and storage within a catchment. These techniques include monitoring water and sediment fluxes at the basin outlet, the identification of primary suspended sediment sources, and the use of ^{137}Cs measurements to document soil redistribution rates and deposition within sediment sinks. Assembling and integrating these three sets of information permits an integrated analysis that establishes a sediment budget for the study area.

The ^{137}Cs technique has been successfully applied in erosion investigations in many areas of the world. Even though ^{137}Cs concentrations are very low in many areas of southern South America, exploratory studies in the region involving this technique have proved promising (Bacchi *et al.*, 2003; Corechel, *et al.*, 2006, Schuller *et al.*, 2003, 2004, 2007). However, there have, to date, been very few studies in South America that seek to link this technique with establishing a sediment budget at the catchment scale.

The study reported in this contribution aims to explore the use of the ^{137}Cs technique in establishing a sediment budget for a rural catchment located in the steep basaltic terrain of southern Brazil. The study also considers modifications to the sampling procedures, and the conversion models employed, for purposes of contributing to the future development of this approach.

THE STUDY AREA

The study area is located on the southern edge of the southern plateau of Brazil (28°49′30″W, 52°12′29″S) (Fig. 1). The area is underlain by acidic basaltic rocks, and because of intense erosion, the terrain is characterized by steep slopes and deep narrow valleys. The soils are dominated by chromic alisols, haplic cambisols and litholic neosols. According to Köppen (1946), the climate is Cfb, subtropical super-humid mesothermic, without a dry season, and a well-distributed average annual rainfall of 1605 mm. The local rainfall erosivity index is 6540 MJ mm ha^{-1} h^{-1} year^{-1}, which is classified as moderate to strong.

Agricultural activity in the region is characterized by small farms producing tobacco, wood, and food crops (e,g. corn, beans, milk, meat, and tea). In general, the region is characterized by high levels of rural poverty. The fragility of the environment, in conjunction with current land use and management systems, causes natural resource degradation (soil and water). High erosion rates (>50 t ha^{-1} year^{-1}) and high sediment yields (>150 t km^{-2} year^{-1}) indicate a severe hydrological and erosional imbalance caused by inadequate soil use and management (Merten *et al.*, 2010).

The study was carried out in the small experimental Arvorezinha catchment (1.19 km^2) that has been used for scientific investigations and teaching, with a focus on the analysis of land use and management impacts on runoff generation, sediment yield, and water quality. Precipitation, flow, and suspended sediment concentrations have been monitored in the catchment since 2002 using automatic equipment (raingauges, linnigraph, and turbidimeter) in conjunction with manual monitoring during storm events.

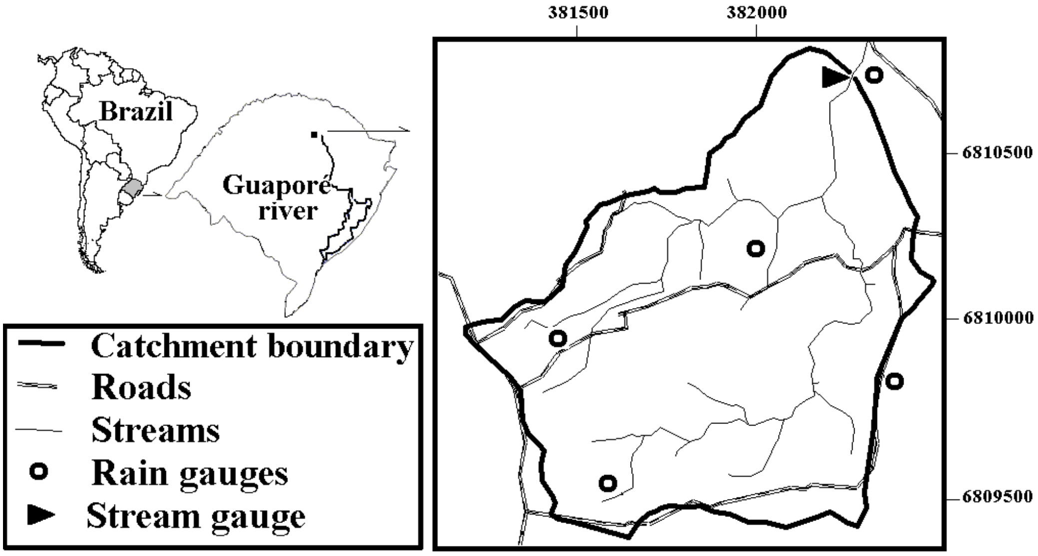

Fig. 1 The location of the Arvorezinha experimental catchment (based on Minella *et al.*, 2008).

THE SAMPLING STRATEGY FOR ^{137}Cs INVESTIGATIONS AND ASSOCIATED DATA ANALYSIS

The validation of physically-based and spatially distributed erosion models (LISEM, WEPP) requires both data collected from the outlet of a catchment, as well as data related to the spatial distribution of erosion and deposition within a catchment (Hessel *et al.*, 2003). Studies using environmental tracers represent one of the few alternatives to the direct measurement of sediment redistribution on a slope or within a catchment. Tracing techniques based on ^{137}Cs exploit the strong adsorption of this fallout radionuclide by surface soils and its potential for evaluating post-fallout redistribution to trace the movement of soil and sediment within the landscape.

The ^{137}Cs technique to study soil redistribution in a study catchment requires a sampling strategy aimed at characterizing the range of slopes, and zones adjacent to river channels, that are representative of different landscape units and cropping systems. The information provided for these landscape units may then be extrapolated to the entire catchment. On each slope selected for sampling, a transect extending from the top of the slope to the river channel was established and samples were collected at points along the transect to provide representative information on the complex pattern of slope erosion and deposition. Seventeen different slopes were selected for sampling, and seven to eight samples were collected from each transect. Twelve additional sampling points were also identified at other locations that were judged to be representative of erosion and deposition hotspots. The locations of the sampling points and transects within the Arvorezinha catchment are shown in Fig. 1.

At the sampling points along the transects, composite bulk cores were collected using a 33.2 cm^2 core tube to a depth sufficient to include the full ^{137}Cs inventory (i.e. ≥25 cm). Three replicate cores were collected within a radius of 2 m, centred on each sampling point. The 12 additional sampling points, scattered across the catchment, selected to be representative of areas of erosion and deposition, comprised four locations with evidence of severe erosion, and eight locations with clear evidence of deposition. The cores collected from these sampling points were sectioned at 2 cm increments to provide information on the reference inventory. Thirty-four bulk cores, and several sectioned cores, also were collected from two reference sites located close to the catchment. These sites were characterized by flat topography and native vegetation, and had not been cultivated for at least the previous 50 years (Fig. 2).

All samples were dried, sieved (<2 mm) and sent for analysis to the Radiometry Laboratory of the Department of Geography at the University of Exeter, UK. Analysis was undertaken by gamma spectrometry using an HPGe gamma spectrometer. The measurement procedures follow those described by Zapata (2002). The ^{137}Cs measurements obtained for the sampling sites were used in a numerical conversion model, the Simplified Mass-Balance Model (Walling *et al.*, 2002),

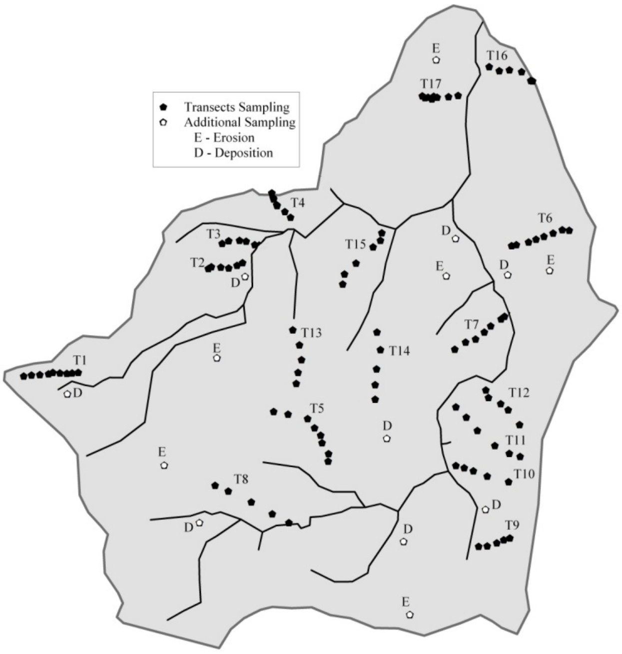

Fig. 2 The location of the ^{137}Cs sampling transects and additional sampling sites within the Arvorezinha experimental catchment.

to estimate erosion and sedimentation rates. This model overcomes some of the limitations of the Proportional Model by considering changes in the ^{137}Cs content in the soil profile over time in response to fallout input, losses due to erosion, additions due to deposition, and progressive incorporation due to tillage of soil from beneath the original plough horizon as the soil depth is reduced by erosion. To estimate the mean annual soil loss or deposition (t ha^{-1} year^{-1}) the model requires information on: the percentage reduction or increase in the total ^{137}Cs inventory, relative to the reference inventory; the average plough depth or thickness of the cultivated horizon (cm); the bulk density of the soil (kg m^{-3}); a particle size correction factor; the time (year) since the onset of ^{137}Cs fallout; and the decay constant for ^{137}Cs (year^{-1}).

The model results for the hillslopes and the meadows near the river channel were extrapolated to the entire catchment by identifying landscape units that were geomorphologically similar to those associated with the sampling sites. This process was assisted by reference to topographic maps of the study catchment, field surveys and the spatially distributed output provided by the LISEM erosion simulation model. The latter provided confirmation of the areas expected to be characterized by high erosion and substantial deposition. This extrapolation made it possible to estimate the mean annual gross erosion (E) and deposition (D) for the catchment. These data were used to derive estimates of the mean annual sediment yield (SY = E – D) and the sediment delivery ratio (SDR = SY/E).

The estimates of sediment yield obtained from the differences between gross erosion and deposition rates, were compared with the mean annual SY measured at the catchment outlet. The latter value was based on nine years of continuous data (2002–2010) which incorporated both wet and dry years, with different conditions of land use and management (Merten *et al.*, 2010). As such, it was considered representative of recent decadal sediment response in the study catchment.

RESULTS AND DISCUSSION

The average ^{137}Cs inventory for the reference sites was 397±21% Bq m^{-2}. Although the coefficient of variation (CV) is relatively high, it is assumed that the mean inventory provides a representative estimate for the reference sites in the study area because of the large number of samples (34) involved. Figure 3 presents representative examples of the ^{137}Cs depth distribution for the reference sites (Fig. 3(a)), eroding sites (Fig. 3(b)), and depositional sites (Fig. 3(c) and (d)). The depth distributions of ^{137}Cs documented for the depositional areas indicate that ^{137}Cs is found well below the plough depth (Fig. 3(c) and (d)), and confirms that substantial deposition and sediment storage occurs at the foot of slopes where the gradient becomes flatter. These depositional areas can be expected to exert a significant "buffering effect" by reducing the transfer of soil remobilized by erosion processes from the steeper areas of the catchment to the channel system.

The results obtained from the individual slope transects indicate substantial variations in ^{137}Cs inventories both between the transects and along the transects. However, a number of recurring features were identified. In general, low ^{137}Cs inventories were found on the shoulders and the slopes, and higher inventories at the bases of slopes in the flatter areas adjacent to the river channel. This pattern confirms the utility of ^{137}Cs inventories for providing information on the spatial distribution of erosion and deposition within the study catchment. The average ^{137}Cs inventory recorded for samples collected from areas with evidence of erosion was 171 Bq m^{-2} and the average inventory recorded for samples collected from depositional areas was 730 Bq m^{-2} with a maximum of 1224 Bq m^{-2}. These results also confirm the importance of landscape characteristics in controlling the redistribution of soil within the catchment as well as the sediment yield at the catchment outlet.

We have found four different patterns of ^{137}Cs inventory variations along the downslope transects. All 17 transects approximately fit one of the patterns, with five similar to T8, five similar to T16, four similar to T1 and three similar to T3 (Fig. 4). All four patterns demonstrate a significant increase in ^{137}Cs activity at the bases of the slopes and in the areas adjacent to the river channel, which reflects sediment deposition. Five transects in these areas (T3, T4, T6, T7, T11)

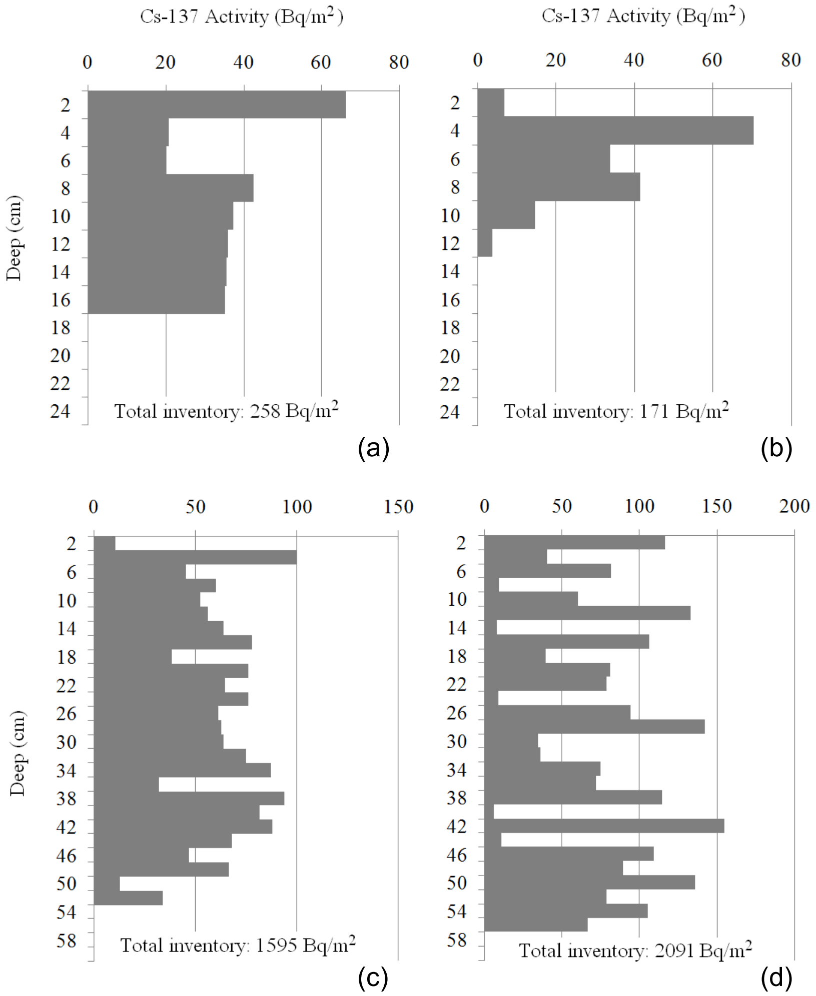

Fig. 3 Representative depth distributions of ^{137}Cs areal activity for the reference area (a) and areas characterized by erosion (b) and deposition (c) and (d).

provide inventories greater than 700 Bq m^{-2}. Another characteristic is that several of the hillslopes provide evidence of erosion extending to the top of the slope, despite the lower slope gradients and limited upslope contributing areas found at these sites. Nine of the 17 slopes exhibit this pattern (T1, T2, T4, T5, T6, T11, T14, T15, T16) that is represented by slopes T6 and T16 in Fig. 4. This shows that cultivation practices (tillage erosion) exert an important influence on the pattern of soil redistribution on the slopes of the study catchment. A third important feature, found in 16 out of the 17 sampled transects, is the presence of increased ^{137}Cs inventories in the middle portions of the slopes. These provide evidence of deposition, but inventories decrease downslope of these areas until they increase again at the foot of the slope and adjacent to the river channel. This feature suggests either that downslope sediment transfer is controlled by the transport capacity of the flow and sediment supply, or that the pattern of erosion is influenced by cultivation practices (tillage erosion). The magnitude of the ^{137}Cs inventories associated with the individual transects is relatively similar in the areas of erosion and deposition in the middle of the slope transects, but greater variation is found in the areas of deposition at the base of the slopes or close to the river channel.

In applying the mass-balance conversion model, 12 cm was considered a meaningful estimate of the mean depth of soil mixing caused by tillage during the ~50 year period (1958–2009) covering maximum ^{137}Cs fallout to the time when the samples were collected. The results indicate an average deposition rate of 76 t ha^{-1} year^{-1} and an average erosion rate of 41 t ha^{-1} year^{-1}, for the sampled points (Fig. 4).

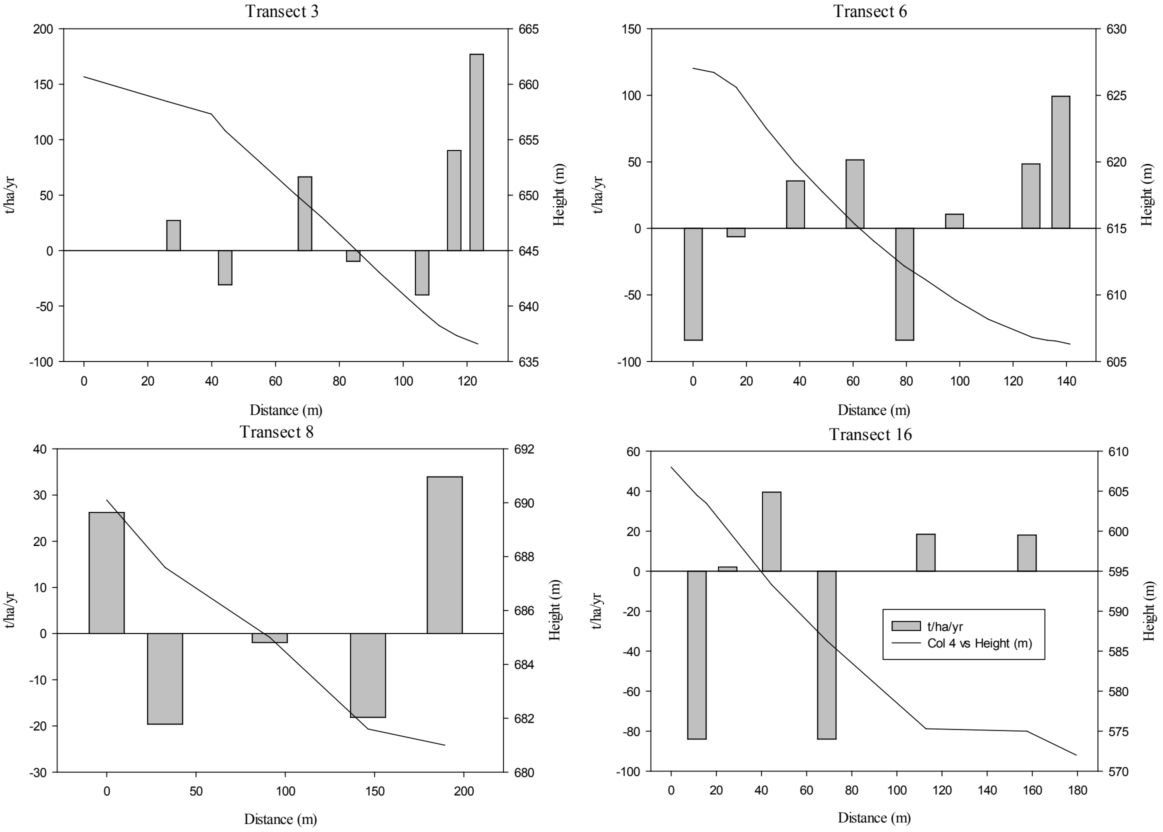

Fig. 4 Estimates of erosion and deposition rates for the sampling points along four of the transects in the Avorezinha catchment.

Estimates of mean erosion and deposition rates (t ha^{-1} year^{-1}) obtained from the 17 transects were extrapolated to the entire catchment, based on landscape units and land use. As indicated above, this extrapolation was aided by field surveys, topographic maps and output from the LISEM model. Areas of significant erosion and deposition were mapped to enable the determination of the total area of the catchment affected by significant erosion and deposition. Further, combining these data with the estimates of erosion and deposition rates obtained from the transects provided a measure of the gross erosion and deposition occurring in the entire study catchment (t year^{-1}). This approach only takes account of soil loss from agricultural areas, and does not include erosion from unmetalled roads and tracks nor channel erosion. Further, it focuses on areas with appreciable erosion and associated areas of deposition, and assumes that other catchment areas are of limited importance as sediment sources.

Mapping the catchment indicates that about 26 ha (22% of the total) was subject to significant erosion whereas significant deposition occurred over 12 ha (10% of the total). Thus, the gross erosion from the catchment was estimated to be 1100 t year^{-1}, and the total deposition 900 t year^{-1}. Thus, the net sediment flux or sediment yield (SY) at the catchment outlet, which represents the difference between gross erosion and deposition, is estimated to be 160 t year^{-1}. Based on these results, the Sediment Delivery Ratio was estimated at approximately 15%. This value may be an underestimate because additional sediment contributions from the roads and channel network, and the parts of the catchment outside the areas with appreciable erosion were not included. On the other hand, failure to include all depositional areas could mean that it may be an overestimate. Finally, the SY value estimated from the ^{137}Cs measurements (SY_{Cs}) was compared to the measured SY value for the catchment outlet (SY_{mon}). The mean annual SY_{mon} value for the 2002 to 2010 period was 130 t year^{-1}, (minimum of 40 t year^{-1} in 2006 and a maximum of 225 t year^{-1} in 2003). Based on this comparison, SY_{Cs} differs from SY_{mon} by only +25%.

CONCLUSIONS

1. The consistency of the SY estimates obtained by monitoring at the basin outlet with those based on the ^{137}Cs budget suggest that the radionuclide technique affords an effective means of documenting catchment-scale sediment budgets.
2. The results obtained from the ^{137}Cs measurements highlight the existence of depositional zones in midslope areas; this may reflect downslope variations in the balance between transport capacity and sediment supply, or possibly, the effects of soil redistribution by tillage.
3. The study highlights the importance of the lower slopes and areas adjacent to the stream channels as sediment sinks that intercept a substantial portion of the soil mobilized from the catchment slopes.
4. This situation implies that the wetlands near the river channel should be preserved, and a cover of native vegetation maintained, rather than the frequent local practice of cultivation, to retain their function as effective sediment traps.

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