The effects of soil conservation on sediment yield and sediment source dynamics in a catchment in southern Brazil

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Abstract This paper presents a synthesis of results from a hydrosedimentometric monitoring programme in a small rural catchment (1.19 km^2) that has undergone significant changes in soil management, which have altered sediment yield and source dynamics. The study is based on repeated surveys of land management, rainfall, water discharge, and sediment yield, as well source tracing investigations undertaken over a period of seven years. During this period, the catchment has undergone a transformation in soil management. Erosion rates in the farmed areas have responded to these management changes, with an almost 75% reduction in sediment yield compared with pre-management conditions. The primary sediment sources in the catchment include cropped fields, unpaved roads, and natural channels. Sediment source dynamics demonstrate significant contrasts between the periods before and after the introduction of conservation practices.

Keywords soil conservation; sediment yield; catchment monitoring; tobacco cultivation; sediment source tracing

INTRODUCTION

The mean annual discharge of Brazilian rivers is of the order of 5660 km^3, which corresponds to approximately 12% of the world's 44 000 km^3 total water supply (PNRH, 2009). However, problems related to lack of basic sanitation in urban areas, and water erosion in rural areas, have had a negative impact on Brazil's water resources. According to EMBRAPA (2002), water erosion in Brazil is primarily associated with inappropriate land use and has been estimated to have an economic cost of the order of US$4 billion annually due to reduced productivity and problems related to siltation of ports and navigable waterways. Of the total amount of sediment mobilized each year by erosive processes, it has been estimated that approximately 600 000 000 t of sediment are transported to coastal areas (Lima *et al*., 2005). However, the flux of sediment to the Brazilian coast has been decreasing in recent decades due to the construction of more than 200 large-scale reservoirs, mostly in the Parana River basin (Stevaux *et al*., 2009).

Although there is little information available in Brazil to evaluate temporal changes in sediment flux, it is believed that the amount of sediment supplied to Brazilian rivers has been increasing, mostly due to changes in land use over the past 10 years (Merten *et al*., 2009). The expansion of the agricultural frontier toward areas considered ecologically important, such as the Amazon region (Costa *et al*., 2003), and the cultivation of areas not suited to agriculture, as is common in some parts of southern Brazil, has contributed to a rapid change in hydrological and sedimentological conditions and a decline in the water quality of Brazilian rivers.

In southern Brazil, problems related to erosion mainly have occurred in areas considered to have low agricultural potential since most of the areas with higher agricultural potential are cultivated using no-till systems (Bollinger *et al*., 2007). Most of the areas considered to have low agricultural potential are located on the edge of the basalt plateau. The native vegetation in these areas was Atlantic Rainforest, which was cleared for conversion to agriculture early in the 20th century. The conditions which limited the use of these areas for agriculture included a combination of steep slopes and shallow, rocky soils. However, many of these areas are considered hydrologically important due to the presence of large numbers of South Atlantic and Uruguay basin headwater streams.

Major agricultural production on the basalt slopes of southern Brazil includes intensive pig farming in integrated agro-industrial systems, and the cultivation of wine grapes and tobacco. Particularly in the case of tobacco, negative environmental impacts are caused by the continuous loss of soil productivity due to water erosion. High rainfall intensity, associated with periods of soil tillage, together with the region's steep hillsides, leads to wide-scale erosion. Traditional management techniques used by tobacco farmers typically involve intensive soil tillage, the use of large quantities of fertilizers, and the intensive application of pesticides. Under these conditions, studies have shown that during rainfall events, significant amounts of sediment, phosphorus, nitrogen and pesticides are transported to rivers (Pellegrini, 2005; Kaiser, 2006; Goncalves, 2007; Minella *et al.*, 2009).

To reduce this problem, changes in tobacco farming practices have been proposed; these involve the introduction of conservation practices such as minimum till and no till. The effects of changes in soil management on sediment yield at the scale of a small catchment (1 km^2) have been studied by the authors since 2001 through continuous hydrosedimentological monitoring, which has combined traditional monitoring with sediment source tracking techniques (Minella *et al.*, 2008, 2009). This study seeks to analyse the temporal variability of sediment yields, to investigate the effects of uncontrollable variables such as annual rainfall, as well as changes in land use, on annual sediment yields.

THE ARVOREZINHA EXPERIMENTAL CATCHMENT

Catchment characteristics

The Arvorezinha Experimental Catchment was established in 2001 as part of the Program to Combat Rural Poverty in the state of Rio Grande do Sul (Fig. 1). It was part of a catchment monitoring project that used environmental variables to assess the impact of this Program. A number of variables were studied, but this paper focuses on sediment yield. The drainage area of the catchment is 1.19 km^2, and the individual farms range from 5 to 20 ha in size. The catchment's steep slopes are one of the factors leading to high erosion potential.

The terrain in the upper portion of the catchment is rolling, while the mid and lower portions are steeper, with an average slope of 9%. The local geology is characterized by extrusive basalts; the soils within the catchment are dominated by chromic alisols, haplic cambisols, and litholic

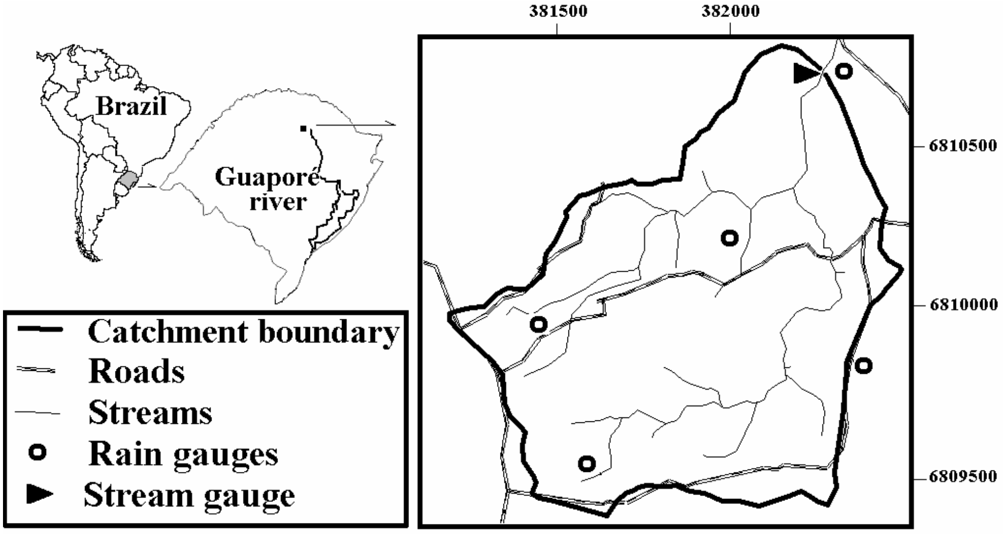

Fig. 1 The location of the Arvorezinha Experimental Catchment (Minella *et al.*, 2008).

neosols. Average temperatures during the hottest month are less than 22°C and during the coldest month greater than 3°C.

Annual precipitation varies between 1250 and 2000 mm. Rainfall volume is well distributed throughout the year, with no well defined dry or rainy season. The local erosivity index is 6540 MJ mm ha^{-1} h^{-1} year^{-1}, which is classified as moderate to strong (Argenta *et al.*, 2001). Despite the relatively even distribution of annual rainfall, erosivity is significantly higher during the months of September and October. This coincides with soil preparation activities prior to tobacco planting, which promote erosion.

Traditional soil preparation by tobacco producers is characterized by intensive soil tillage and the heavy use of chemical fertilizers and other agro-chemicals. During the second year of monitoring, rural extension officers introduced conservation tillage practices that were gradually adopted by the producers. The new management strategies aimed to minimize soil tillage, promote the use of contour planting, and substituted winter fallow by cover crops such as black oats, vetch and forage parsnip. The minimum till system was chosen as the best alternative to a transition to no-till. Minimum tillage is characterized by the use of cover crops and contour ploughing and planting. Using these practices, the soil remains over 70% covered. The adoption of minimum till practices by the farms in the Arvorezinha catchment was gradual. It began in the spring of 2003 and increased to 96% in 2008 (Table 1).

Table 1 Percentage change in land use and soil management in the Arvorezinha catchment over the study period.

	Fallow, pasture, native forest and reforest	Field crops (tobacco and corn):	
		Conventional management	Conservation management
2002	67.9	32.1	0.0
2003	55.9	44.1	0.0
2004	49.3	29.7	21.0
2005	38.6	42.3	19.1
2006	36.0	20.8	43.2
2007	58.0	12.0	30.0
2008	59.5	1.7	38.8

Monitoring

Responses to soil management changes were evaluated by monitoring key variables related to erosion and sediment yield in the catchment. These included: (a) precipitation, which controls the erosive energy and the volume of rainfall and runoff associated with each event; (b) spatial and temporal variability of land use and management practices, representing the agricultural evolution of the catchment; (c) water discharge and suspended sediment concentration, which integrate the effects of climate, land use, and management; and (d) geochemical tracers present in soils and sediment that make it possible to determine the spatial and temporal variability of sediment sources in the catchment.

Monitoring occurred from 2002 to 2008, and represented seven tobacco production cycles. During this period, the rainfall events, land use, and management practices were intensively monitored. Based on analysis of these events, it was possible to determine how the changes in land use and management affected hydro-sedimentological responses in the study catchment. Water discharge was determined by continuous monitoring of stage within a Parshall flume using a pressure sensor. A recording interval of 10 minutes was used and this provided adequate characterization of the rising limb. Suspended sediment concentration monitoring was based on the manual collection of samples during flood events using a US-DH-48 sampler, and continuous monitoring of turbidity using a probe installed near the flume. Every effort was made to collect suspended sediment samples from the maximum possible number of flood events. This was made possible by the almost continuous presence of a technician. The 10-minute turbidity record was used to estimate suspended sediment concentrations for events where manual samples were not collected. The data used for model calibration comprised concurrent instantaneous in-stream measurements of turbidity, streamflow, and suspended sediment concentration that corresponded to paired turbidity and streamflow measurements (Minella *et al.*, 2008).

Sediment discharge (mass per unit of time) was estimated by multiplying the instantaneous flow rate (L s^{-1}) by the suspended sediment concentration (g L^{-1}), using the sampled sediment concentrations and the monitored flow rate during rainfall events. Event sediment yields (SY) were estimated by integrating the sediment discharge curve over time (equation (1)) (Walling & Collins, 2000):

$$SY = K\sum_{i=1}^{n}\left[Cs_i Q_i\right] \tag{1}$$

where Cs is the suspended sediment concentration; Q is the flow rate; and K is a conversion factor for units and periods of time.

In addition to sediment yield at the catchment outlet, the source of the sediment also was evaluated using a fingerprinting approach (Collins *et al.*; 1997; Walling, 2005; Minella *et al.*; 2008). The technique uses the properties of the sediment to establish its source by comparing them with the equivalent properties of potential sources. Information on sediment source provides an improved understanding of the catchment sediment dynamics (Collins *et al.*, 1997). Briefly, the steps in obtaining quantitative information on sediment source are as follows: (a) identification of potential sources; (b) sampling; (c) chemical and physical characterization of sediment and source materials; and (d) quantification of the relative contribution from the different sources. Information on annual sediment yields and sediment sources was assembled during the study to link changes in land use and soil management to changes in erosion and sediment yield.

RESULTS AND DISCUSSION

The data presented in Table 1 show that there were significant changes in land use and soil management over the course of the monitoring period (2002–2008), with changes in soil management being more important than those in land use (Figs 2 and 3). Changes in land use, which began about halfway through 2002, involved tobacco cultivation of former fallow areas due to increases in international tobacco prices. Fallow, pasture and forest areas decreased until 2006, at which point these areas expanded again, especially for forests to provide firewood used in tobacco processing.

Despite the significance of land-use changes, altered soil management was more important in affecting erosion. In 2003 and 2004, the rural extension agency (EMATER) actively encouraged producers to adopt soil conservation practices, which led to a gradual shift from conventional to conservation management (Fig. 3).

The adoption of minimum till practices by producers has been gradual and has still not reached 100% in the tobacco cultivation areas. The reasons are related to soil characteristics, such as the presence of subsurface layers that impede drainage and poor aeration, which sometimes make minimum till management problematic. Another factor that sometimes restricts the expansion of minimum till has been the climate. In years in which the autumn and winter are dry, cover crops, such as black oats, vetch and forage parsnips, do not develop well. In addition, cover crops often are used by farmers as animal feed. With the removal of part of the biomass, there sometimes is not enough left to meet no-till or minimum till requirements. However, monitoring has shown a clear and significant increase in the areas under conservation tillage.

Another important point is that the soil conservation practices that have been adopted to date have been limited to tillage reductions and the use of cover crops. Other practices that would help control surface runoff from high-magnitude rainfall events, such as terraces and vegetated contour strips, have not yet been introduced. The use of mechanical structures to control surface runoff,

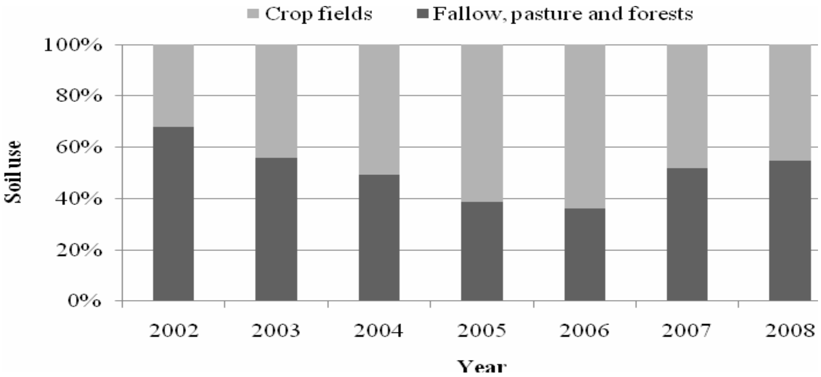

Fig. 2 Changes in land use in the Arvorezinha catchment during the study.

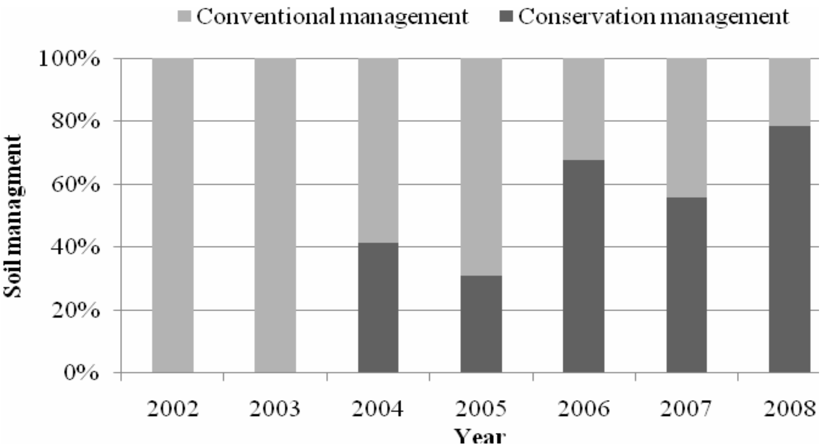

Fig. 3 Changes in soil management in the Arvorezinha catchment during the monitoring period.

and especially the restoration of riparian buffer strips, have met with considerable producer resistance. Nevertheless, they have recognized the importance of minimum till practices in both erosion control and in making their work easier. These two factors have been key in promoting the adoption of minimum till practices by the farmers.

The effect of land use and soil management changes on erosion within the catchment can be seen in the reduction of annual sediment yield (Fig. 4).

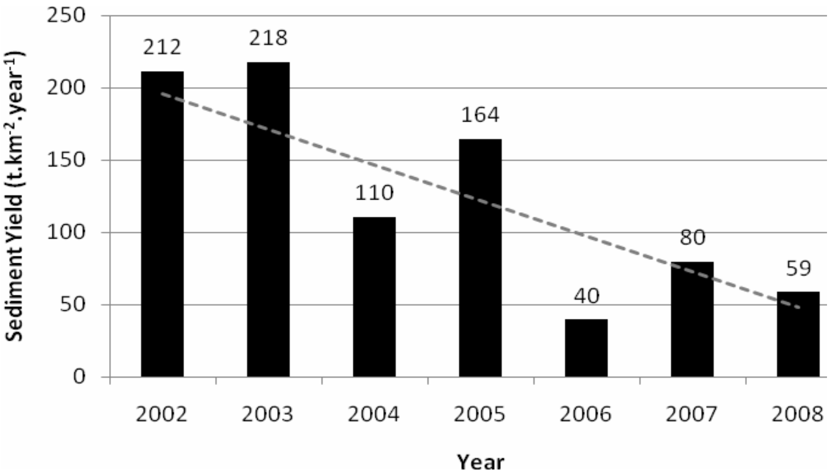

Fig. 4 Changes in annual sediment yield from the Arvorezinha catchment over the monitoring period.

The 75% reduction in sediment yield since the beginning of the monitoring period is mostly due to the reduction of erosion from cultivated fields. Minimum till practices and contour planting have significantly reduced soil mobilization and transfer to river channels. These effects have been particularly noted for low and medium magnitude events. For high magnitude events, minimum tillage plus contour planting has proven insufficient to control erosion, especially in areas with higher slopes. In these locations, mechanical erosion control practices, such as terraces under permanent vegetation, appear necessary. In addition, restoration of riparian zones is critical, as these are currently highly degraded throughout the catchment.

One concern raised by this study has been the need to isolate the confounding influence of variations in annual rainfall on sediment yield. Studies carried out at the catchment scale under naturally occurring climatic conditions are subject to interannual variability that can make it difficult to isolate the impact of this factor. Table 2 shows the variability of annual rainfall over the 7-year monitoring period. Mean annual precipitation for the period was 1751 mm, slightly higher than the long-term average of 1540 mm. The coefficient of variation for the study period was 19%.

In an effort to make it easier to visualize the effect of changes in soil management during the study, the annual data were grouped (summed) into two-year clusters (Fig. 5). Since wet and dry years alternated after 2003, each cluster includes a dry year followed by a wet year. There does appear to be a significant reduction in sediment yield for periods with similar rainfall (Fig. 5).

Table 2 Total yearly rainfall in the Arvorezinha catchment during the study period.

Year	2002	2003	2004	2005	2006	2007	2008	AVG	CV
Rainfall (mm)	2220	1835	1324	1935	1409	2026	1508	1751	19%

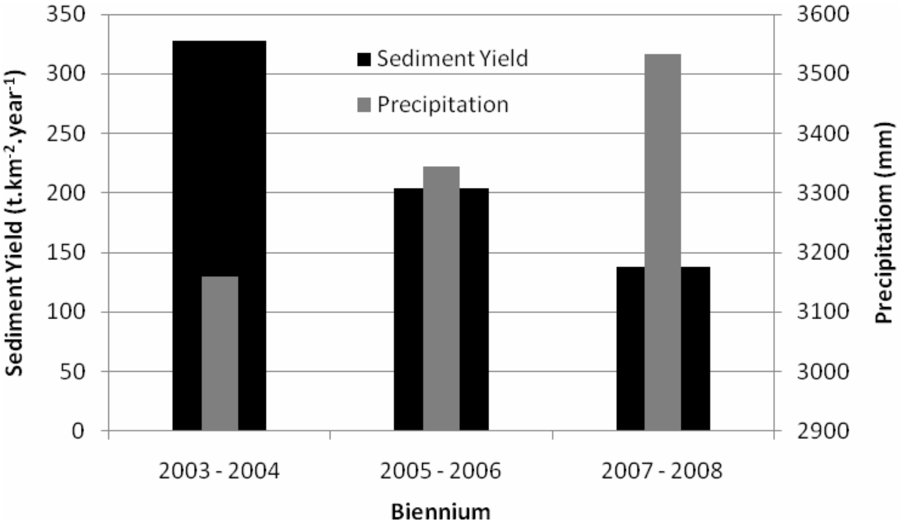

Fig. 5 Reduction in sediment yield for periods with similar rainfall.

Although the reduction in catchment sediment yield was primarily caused by the application of conservation practices in the cultivated areas, the relative importance of different sediment sources also changed over the study period. These changes were determined by a sediment source identification study. Table 3 shows the temporal variability of the three primary sediment sources in the catchment. On the left side of Table 3 are the relative contributions of each source to total sediment yield, and on the right side is the value converted to t km^{-2} $year^{-1}$, obtained by multiplying the relative contribution of each source by the total biannual sediment yield.

The results presented in Table 3 show that at the beginning of the project (2002–2003), the predominant sediment source was crop fields, with a sizeable contribution from roads, and only a

Table 3 Changes in the relative and absolute contributions from the different sediment sources in the Arvorezinha catchment during the study period.

	Relative sediment contribution (%)			Sediment yield from each source			Sediment yield
	Crop fields	Roads	Channels	Crop fields	Roads	Channels	
		%			(t km^{-2} year^{-1})		(t km^{-2} year$^{-1)}$
2002–2003	62.6	35.6	1.8	268.8	152.9	7.7	429.4
2004–2006	53.8	24.2	22.0	169.0	76.0	69.1	314.1
2007–2008	69.2	14.4	16.4	95.6	19.9	22.7	138.2

small contribution from stream channels. After implementing conservation measures over approximately 40% of the catchment (2004–2006), field contributions decreased while that from stream channels increased. In 2007–2008, the crop fields were once again the predominant sediment source, but with a similar contribution from roads and channels; a contrast to the first two years.

It is important to recognize that evaluating changes in the magnitude of erosion and sediment yield by looking only at relative source contributions over the period is insufficient. Changes in sediment response are likely to reflect changes in both the magnitude of sediment yield and the relative contribution of the sources. Hence, the relative source contributions were multiplied by the sediment yield for that period to quantify the contribution from each source during each period. This provides a useful representation of the spatial and temporal dynamics of the source contributions to the total sediment yield for the catchment (Fig. 6).

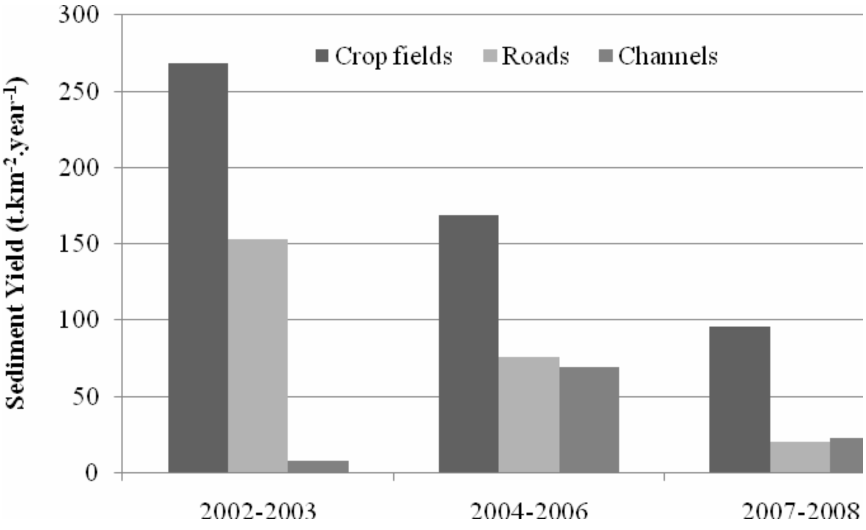

Fig. 6 Changes in the sediment yield associated with the individual sediment sources over the study period.

The implementation of soil conservation practices in the Arvorezinha catchment occurred gradually, and did not reach 100% of the tobacco-producing areas. Nevertheless, it generated important changes in the magnitude and pattern of erosion processes that were reflected in the annual sediment yield. There was a significant decrease in the mobilization of sediment from the crop fields and roads, and a different behaviour for sediment mobilized from the stream channels. In terms of the roads, even though they were not the subject of specific erosion control measures, there was less sediment mobilized due to less water runoff from the fields, because more water was retained in the fields due to minimum tillage and contour planting.

However, erosion within the channel network displayed behaviour different to the other sources. Prior to the implementation of conservation practices, there was only a very minor sediment contribution from this source, but this increased significantly after conservation measures were introduced. Minella *et al.* (2008) suggested that this effect was related to a reduction in sediment supply coming from the fields into the channels. To compensate for the reduction in sediment supply, the runoff energy that had previously been used to transport this sediment was now available for within channel erosion.

Later, in the third biennium, with the expansion of conservation practices in the crop field areas, the contributions from all sources was slightly reduced; however, relative to the channel and road sources, field contributions grew.

CONCLUSION

The primary conclusion reached by this study is that implementing soil conservation practices in a small rural catchment characterized by intensive agricultural activity, steep slopes, shallow soils, and high rainfall led to a reduction in sediment yield on the order of 75% (from 200 t km^{-2} $year^{-1}$ to 50 t km^{-2} $year^{-1}$). These results were obtained using a combination of minimum till management, cover crops, and contour planting on about 80% of the area under tobacco cultivation. It can be further assumed that the values for sediment yield could have been even lower if other mechanical erosion control practices had been implemented to reduce surface runoff. Further, the erosion processes that operate in the channel network reflect a complex interaction with the processes operating on the catchment slopes.

The processes observed in the Arvorezinha catchment show that the variability in sediment yield at the catchment outlet integrated various factors that are difficult to separate. During the monitoring period, the years were very heterogeneous, which made it difficult to separate climate effects from conservation effects. Nonetheless, it was possible to clearly see the impact of the measures in reducing erosion and sediment yield. In addition, the application of source identification techniques showed that integrated planning efforts for rural catchments should necessarily include surface runoff control measures for roads, and protection of fluvial riparian zones.

Lastly, this study demonstrates that environmental monitoring projects that seek to evaluate the effects of natural resource conservation at the catchment scale should be based on multiyear data series, and that these data must be collected (whether manually or automatically) with a sampling frequency capable of covering most of the events which occur in a hydrological year. The combination of traditional monitoring and fingerprinting techniques provides sediment source identification and permits investigators to determine from where sediment is coming; this information is important for evaluating the efficiency of soil conservation practices at the catchment scale.

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