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# Combining sediment source tracing techniques with traditional monitoring to assess the impact of improved land management on catchment sediment yields

**Jean P.G. Minella** [a,b], **Des E. Walling** [b,*], **Gustavo H. Merten** [a]

[a] *Institute of Hydraulic Research (IPH), Federal University of Rio Grande do Sul (UFRGS), P.O. Box 15029, 91501-970 Porto Alegre, RS, Brazil*
[b] *Department of Geography, University of Exeter, Amory Building, Rennes Drive, Exeter EX4 4RJ, UK*

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**Summary** This paper aims to demonstrate the potential value of combining sediment source tracing techniques with traditional monitoring approaches, when documenting the impact of improved land management on catchment sediment yields. It reports the results of an investigation undertaken in a small (1.19 $km^2$) agricultural catchment in southern Brazil, which was monitored before and after the implementation of improved land management practices. Attention focussed on 50 storm events that occurred between May 2002 and March 2006 and which reflected the behaviour of the catchment during the pre-change, transition and post-change periods. Improved land management, involving minimum-till cultivation and the maintenance of good crop cover, was introduced in early 2003. The traditional monitoring provided a basis for evaluating the changes in storm runoff volume, storm hydrograph peak and storm-period sediment load and mean suspended sediment concentration. The results indicate that both storm runoff volumes and peak flows associated with a given amount of rainfall provided evidence of a significant decrease after the introduction of improved land management. Storm-period sediment loads showed a similar reduction, with a reduction by as much as 80% for low magnitude events and of ca. 40% for events of intermediate magnitude. However, there was no significant change in mean suspended sediment concentrations, indicating that the reductions in sediment load were primarily the result of the reduced storm runoff volume. Sediment source fingerprinting was used to explore the changes in the relative and absolute contributions to the storm sediment loads from the three key sources,

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[*] Corresponding author. Tel.: +44 1392 263345; fax: +44 1392 263342.
*E-mail address:* d.e.walling@exeter.ac.uk (D.E. Walling).

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namely the surface of the fields under crops, the unpaved roads and the stream channels. A comparison of the load-weighted mean contributions for the pre- and post-treatment periods indicated that the contribution from the field surfaces and unpaved roads decreased from 63% and 36% to 54% and 24%, respectively, whereas the contribution from the stream channels increased from ca. 2% to 22%. By relating the absolute amounts of sediment mobilised from each individual source group to variables representing the runoff and precipitation associated with the events, it was possible to identify changes in the response of the individual sediment sources to the changes in land management that occurred within the catchment. Sediment mobilisation from the stream channel during individual events increased substantially over the whole range of flows after the introduction of improved land management in the study catchment, whereas the amounts of sediment mobilised from the surfaces of the fields and the unpaved roads showed a significant decrease during events of low and intermediate magnitude. The short monitoring period associated with the study, coupled with inter-annual variations in rainfall, necessarily limit the scope and rigour of the study reported, but it is seen to provide a useful demonstration of how the coupling of sediment source tracing with more traditional monitoring techniques can provide an improved understanding of the impact of improved management practices on the sediment response of a catchment, as well as important information to inform the design and implementation of effective sediment management and control measures.

## Introduction

Concern for the impact of accelerated rates of soil erosion on agricultural land, resulting from land clearance and poor land management, has traditionally focussed on their effects in terms of soil degradation, reduced crop productivity, problems of food security, and destruction of an essentially non-renewable resource (e.g. Wischmeier and Smith, 1978; Evans and Boardman, 1994; Lal, 1998). These effects are often termed on-site impacts. Increasingly, however, attention has also been directed to the equally important, and perhaps even more significant, off-site impacts. These include a wide spectrum of potential impacts, which range from reservoir sedimentation and associated siltation of irrigation and other hydraulic structures, through the role of sediment as a diffuse source pollutant, both in its own right and due to its importance in the transport of sediment-associated nutrients and contaminants, to the degradation of aquatic habitats and the adverse impact of fine sediment on freshwater fisheries, particularly through the siltation of fish spawning gravels (e.g. Waters, 1995; Wood and Armitage, 1997, 1999; Acornley and Sear, 1999; Walling et al., 2003). In many areas of the world, control of soil erosion and sediment delivery to watercourses is seen as being of great importance in reducing nutrient inputs to fluvial and lacustrine systems, as well as in reducing diffuse source pollution more generally. In the UK, for example, reduction of soil loss and associated sediment mobilisation and transfer to watercourses is seen as an important component of the recent development of Catchment Sensitive Farming (e.g. DEFRA, 2004). Likewise, in Europe, control of sediment mobilisation and transfer has been increasingly identified as a key requirement under the Water Framework Directive, which aims to restore rivers and other watercourses to a condition commensurate with 'good ecological status' (see Brils, 2005; Owens and Collins, 2006). Similar pressures exist in many developing countries, where sediment is seen as a key pollutant and an important cause of the degradation of both freshwater and marine aquatic ecosystems.

Against this background, there is a growing need to design and implement improved land management strategies, aimed at reducing sediment mobilisation and transfer to watercourses. Whereas much of this technology already exists, or is capable of transfer from traditional soil conservation practices, the focus on off-site impacts means that the installation of buffer strips, both in riparian areas and along transfer pathways, may be as important as increasing on-site infiltration rates and thus reducing surface runoff generation. Equally, there is a need to adopt a catchment wide perspective, since the ultimate aim of many erosion and sediment control programmes will be to reduce downstream fine sediment fluxes. Identifying the primary sediment sources within a catchment, so that the available resources can be targeted at those sources, will frequently be an important requirement. In many situations there will be a need to implement catchment monitoring programmes, in order to assess the impacts of particular land management practices, to demonstrate the cost-effectiveness of implementing control measures and to provide the empirical evidence required to convince local landowners and farmers of the potential benefits of implementing improved or different land management practices.

Traditional catchment experiments (see Toebes and Ouryvaev, 1970; FAO, 1997; Lal, 1988) generally involve measuring the sediment yield at the outlet of a catchment and assessing the impact of changing land management practices on this yield. Such investigations commonly employ either a paired or multiple catchment experiment or a longer-term single catchment (i.e. 'before' and 'after') study and these approaches can provide an effective basis for generating the required empirical evidence. However, the nature of the data provided by such monitoring programmes may preclude addressing key questions linked to the complexity of sediment mobilisation and delivery from agricultural land. For example, the sediment flux at a catchment outlet is likely to comprise sediment derived from several different source types, only some of which may be targeted by control measures, and it may therefore be important to confirm that any reduction in sediment flux reflects a reduction in the contribution from the targeted sources. Furthermore, in some situations a reduction in sediment contributions from the catchment surface could increase the transport capacity of the flow in the channel system and result in increased sediment mobilisation from stream channels, so that the sediment flux at the catchment outlet may show little change, even though significant changes in the relative contributions from different sources have occurred. In view of these complexities in sediment mobilisation and delivery, Walling (2006) has argued that there is a need for new approaches that provide information on the catchment sediment budget and the changes in that budget resulting from changing land management and, more particularly, that sediment tracing techniques (e.g. Foster, 2000) can provide a valuable complement to more traditional monitoring techniques. The study reported in this paper aims to demonstrate how the use of sediment source tracing techniques, in combination with more traditional monitoring techniques, can provide an improved understanding and assessment of the impact of improved land management and sediment control measures in reducing soil erosion and sediment mobilisation and delivery to watercourses. Although source fingerprinting techniques are being increasingly used to establish the relative importance of the main sediment sources in a catchment (see Walling, 2005) the study reported is thought to be the first use of the fingerprinting approach in a dynamic mode, to investigate the progressive changes in source contributions, in response to changes in land management practices.

## The study area and the study catchment

The study area is located on the upper northeast slope of the Rio-Grandense plateau, in the state of Rio Grande do Sul in southern Brazil (Fig. 1). It represents the headwaters of the Guaporé River, a tributary of the Jacuí River. The altitude ranges between 560 m and 720 m and the area is characterised by steeply rolling and rolling terrain with average slopes in the range 4–84% (Minella, 2003). The area is underlain predominantly by basalt, which weathers to produce fertile Entisols and Inceptisols with average depths of about 50 cm (EMBRAPA, 1999). According to the Köppen classification, the climate is subtropical super-humid mesothermic (i.e. Cfb), with cool temperatures in the summer and severe frosts in the winter (Nimer, 1990). The mean annual precipitation is 1605 mm, with this distributed fairly evenly throughout the year. The area is predominantly rural with well-developed agriculture. The agricultural development of the region started around 1925, with the exploitation of tea (Ilex paraguariensis) and wood and the development of subsistence cultivation. The agricultural exploitation of the region gradually intensified and reached its peak in the early 1960s. Aerial photographs from that period show a greater area under agriculture than at present (Lopes, 2006). Over the past four decades, tobacco has been the dominant crop, although maize and wheat are also grown. The area given over to cop production was typically around 35%, but it varied according to the price of agricultural produce. During this period of agricultural exploitation, when soils were inadequately managed and protected, soil erosion was both serious and widespread and large amounts of sediment accumulated along the drainage lines and on the valley floors, changing both the longitudinal and cross-sectional profiles of the channels.

Since the 1990s there has been increasing concern for accelerated soil loss from agricultural land throughout the state of Rio Grande do Sul. Increased rates of soil loss were seen as resulting in depletion of the soil resource and reduced crop yields, as well as increasing diffuse source pollution in the local rivers and streams. Recognising both the environmental and the socio-economic dimensions of these problems, the government included improved land management, aimed at reducing erosion and sediment inputs to watercourses, as a key component of its program against

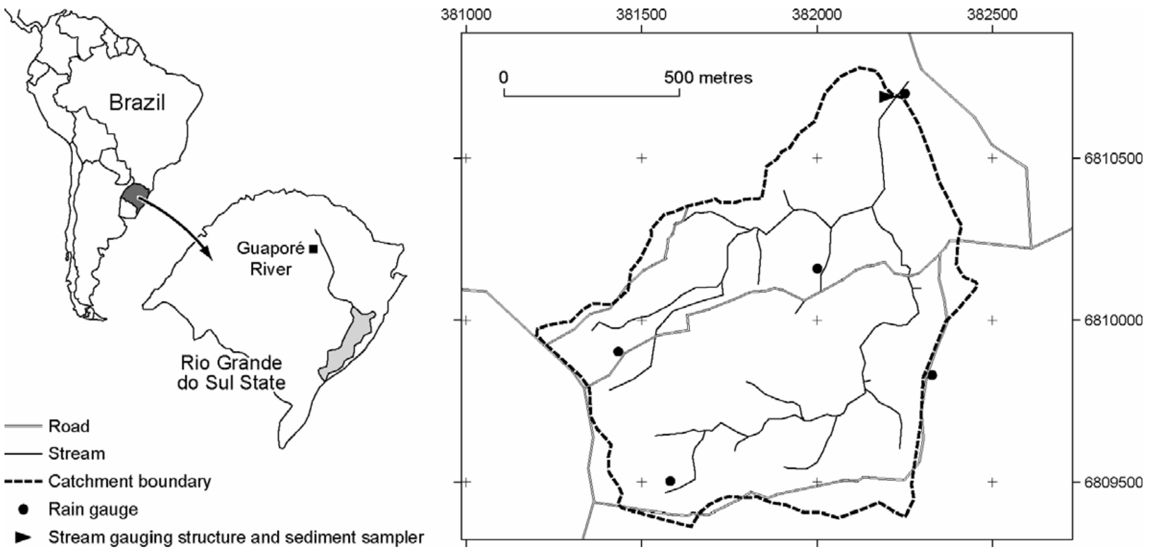


**Figure 1** The location and main features of the of the Arvorezinha catchment.

rural poverty (PARP). This initiative aimed to promote sustainable use of natural resources, environmental protection, increased family incomes and improved local infrastructure. As in many other areas of the world where such erosion control and sediment management programmes have been implemented, the State Government perceived a need to document the impact of the improved land management, in order to evaluate its success, assess its cost-effectiveness and promote its wider and longer-term application (Merten and Minella, 2005a). To meet this need within the study area, the Arvorezinha catchment was selected and instrumented, to document changes in its sediment yield in response to improved land management involving minimum-till cultivation and the maintenance of good crop cover. This work was undertaken as a joint venture between the Federal University of Rio Grande do Sul (UFRGS-IPH), the Federal University of Santa Maria (UFSM-CCR) and the State Government of Rio Grande do Sul (Merten and Minella, 2005b).

The Arvorezinha catchment (Fig. 1), which is seen as being representative of the study area, covers an area of 1.19 km$^2$. In its upper parts, the topography is gently rolling with average slope gradients of ca. 7%, but in its lower parts, which represent about two thirds of the catchment, the topography is more deeply dissected and characterised by shorter steeper slopes (ca. 84%) and steep sided re-entrant valleys, cutting back into the higher land. The average channel slope, determined from the catchment DEM, is 9% and the time to peak for storm runoff hydrographs is typically in the range 20–50 min. Land use within the catchment is predominantly agricultural, with much of the land being used for growing tobacco. Available information suggest that the mean annual suspended sediment yield of the catchment prior to the implementation of improved land management was ca. 145 t km$^{-2}$ year$^{-1}$ (Merten and Minella, 2005b), with suspended sediment concentrations during high magnitude runoff events reaching a maximum of ca. 11,000 mg l$^{-1}$.

The months of greatest rainfall erosivity in the study catchment are September and October, which coincide with the beginning of the planting cycle (Argenta et al., 2001). Under traditional management, the soil cover is minimal from August until November, because the soils are ploughed in August and the tobacco is grown as a rowcrop with weed control between the rows. This condition promotes soil detachment by raindrop impact and surface runoff generation by surface sealing. The cold post-harvest period extending from May to July is associated with relatively low evapotranspiration and high soil moisture status, which reduce the proportion of rainfall that infiltrates and increases surface runoff. The rainfall during this period is commonly of low intensity, but long duration, and can generate events with relatively high sediment yields. The summer season extends from December to March and generally includes lengthy dry periods, although some storms of high intensity but short duration may occur. Storm runoff and sediment loads are relatively low during this period, due to the higher evapotranspiration and infiltration rates, the more limited rainfall and the good soil cover provided by the mature tobacco plants.

The catchment was selected for the investigation and instrumented in early 2002. Its establishment coincided with significant changes in land management promoted by the PARP programme, aimed at reducing soil erosion and sediment transfer to the watercourses. In implementing improved land management practices, emphasis was placed on the introduction of minimum-till cultivation practices and the maintenance of good crop cover, including the planting of cover crops.

Fig. 2 provides further information on the changes in land use within the Arvorezinha catchment over the period April 2002 to March 2006. The land use within the study catchment was documented on a regular annual basis, using field surveys supported by a GPS. The resulting data were input to a GIS using Spring/INPE®, and this permitted the changes in land use associated with individual fields to be recorded. The main land use classes found within the catchment include cropland (primarily tobacco), pasture, fallow land and forests. The 'forest' category includes areas of native forest, small plantations established to supply firewood for drying tobacco and trees in riparian areas bordering the streams. The ''fallow'' category represents agricultural areas where crops have not been grown for 5 years or more, in order to improve soil quality and restore its fertility. These areas are characterised by good soil cover (shrubs, grass and herbs). Based on annual monitoring periods extending from April through to the following March, the following shifts in land use were identified (see Fig. 2).

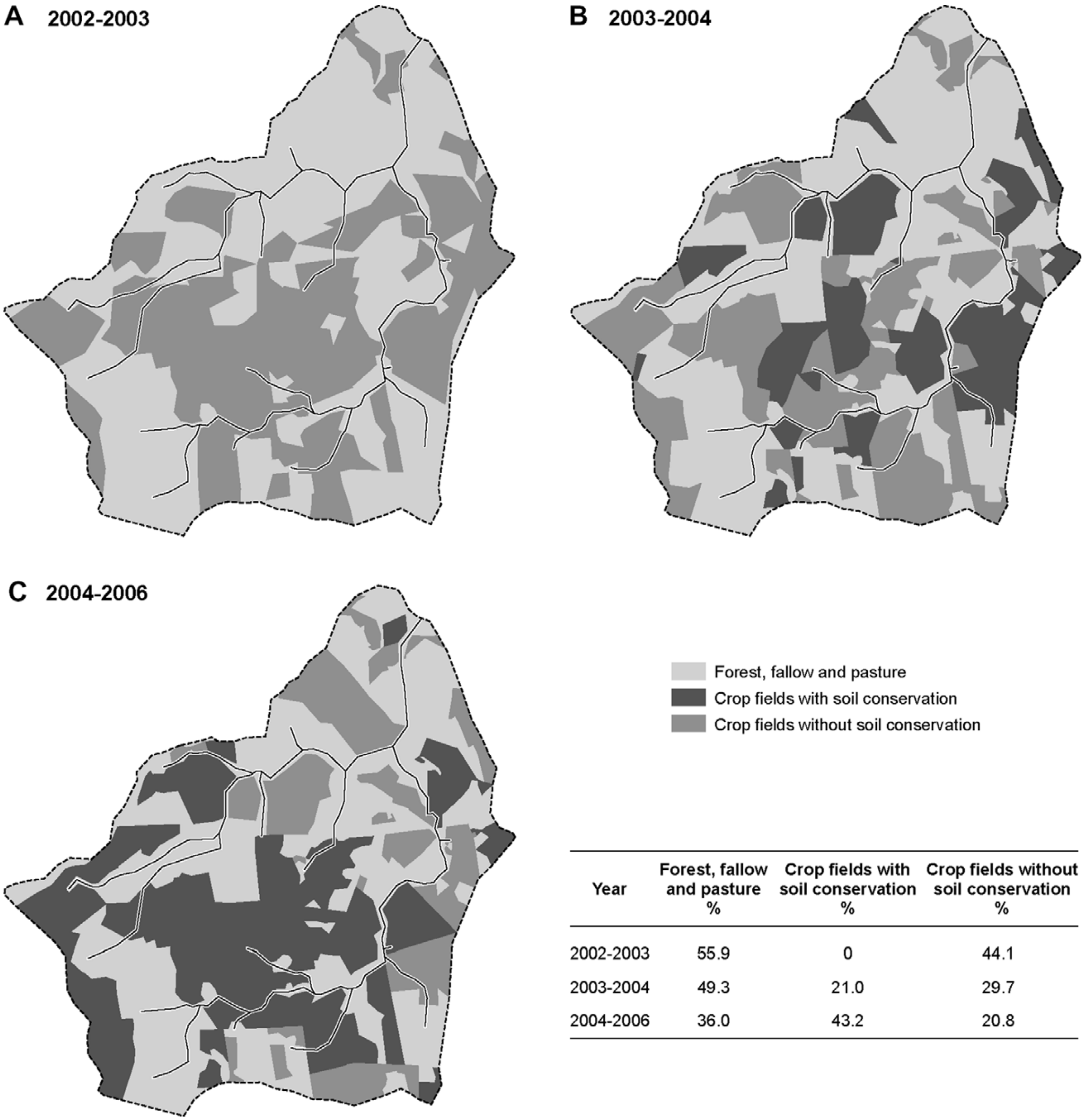
(i) Initial period (April 2002 to July 2003) – stable crop distribution under traditional management.
(ii) Transitional period (August 2003 to March 2004) – progressive implementation of improved land management.
(iii) Improved management period (April 2004 to March 2006) – an essentially stable pattern of land use with a significant proportion under improved management.

## Methods

### Monitoring water and sediment fluxes

The catchment investigation aimed to use the single catchment (before and after) approach to assess the impact of changing land management on water and sediment fluxes at the catchment outlet. In this approach, selected measures of water and sediment flux, derived for individual storm events, are related to rainfall and runoff parameters, so that changes in the resulting relationships associated with changing land management condition can be identified and used to assess the magnitude of the changes in water and sediment flux. In addition, sediment source tracing or fingerprinting investigations (see Walling, 2005) were incorporated into the study, in order to provide further information on changes in the sediment dynamics of the catchment.

The basic hydrological monitoring included an automatic meteorological station, five recording raingauges, and a Parshall flume at the catchment outlet, equipped with a data logger that recorded the stage measured by a pressure sensor at 10-min intervals. Existing information on suspended sediment transport by streams in the study area indicated that substantial sediment fluxes were confined



| Year | Forest, fallow and pasture % | Crop fields with soil conservation % | Crop fields without soil conservation % |
|---|---|---|---|
| 2002-2003 | 55.9 | 0 | 44.1 |
| 2003-2004 | 49.3 | 21.0 | 29.7 |
| 2004-2006 | 36.0 | 43.2 | 20.8 |

**Figure 2** Changes in land use and land management within the Arvorezinha catchment, 2002—2006.

to medium and high magnitude storm runoff events, which, in the Arvorezinha catchment, correspond to storm hydrographs with a peak discharge of more than 800 l $s^{-1}$ and a probability of 0.05 or less in the associated annual frequency distribution. The baseflow discharge of the catchment was typically ca. 50 l $s^{-1}$ with a suspended sediment concentration of ca. 20 mg $l^{-1}$ (Merten and Minella, 2005b). The suspended sediment sampling strategy aimed to cover most of these significant storm runoff events. In the absence of automatic sampling equipment, suspended sediment sampling was undertaken manually at the sampling station located immediately upstream of the flow gauging flume. Depth-integrated samples were collected using a US-DH48 sampler, with a sampling interval of 5—30 min. The sampling frequency depended on the rate of change of water discharge and sediment concentration on the rising and falling limbs of the hydrograph. The aim was to provide a detailed record of the variation of suspended sediment concentration during the event that could be combined with the water discharge record to produce reliable estimates of the sediment flux associated with individual events (Walling and Collins, 2000).

## Sediment source fingerprinting

### Sample collection and analysis

The sediment source fingerprinting investigation incorporated into the study aimed to establish the relative contributions of the main suspended sediment sources within the catchment, to the sediment yield at the catchment outlet. The approach employed was similar to that described by Walling (2005) and involved characterising the potential sediment sources within the catchment by means of a set of fingerprint properties that successfully discriminated between those sources, and establishing their contribution to the sediment yield at the catchment outlet by matching the properties of that sediment to those of the potential sources, using a multivariate mixing model. Potential sediment sources were identified by observing the sediment mobilisation and transport processes operating within the study catchment during storm events and were dominated by three main groups, namely, the surface of the fields under crops, unpaved roads and channel banks. Forty representative georeferenced samples of surface, and thus potentially mobilisable, material were collected from these potential sources at different locations within the study catchment. Areas under pasture, fallow and forest were excluded from the sampling programme, because field observations indicated that they were not significant sediment sources.

The samples of potential source material were collected using a trowel, by obtaining a representative sample of the uppermost layer of the source material (0–0.05 m). In order to ensure that the source material samples were representative of the potential heterogeneity of the individual sources, each sample comprised a composite of 10 sub-samples collected in the vicinity of the sampling point. The amount of material collected for each sample was about 0.5 kg. The samples were dried in the shade and sieved to <150 μm, before being sent for chemical analysis.

The suspended sediment samples required for the source fingerprinting exercise were collected during storm events that occurred during the period between May 2002 and March 2006. A total of 74 samples were collected from 50 individual flood events. For some events, there were two or three separate samples distributed over the hydrograph. The samples were collected using a sampler that was similar in design to a single-stage sampler (FIASP, 1961) with the water being stored in a 40-l plastic drum. Modifications made to this equipment enabled sediment samples to be collected during both the rising and falling limbs of flood events (Minella, 2003). The sediment was recovered from the bulk samples using a continuous flow centrifuge and this was subsequently oven dried at 40 °C and sieved to <150 μm.

Physical and chemical analysis of the suspended sediment samples and the samples of potential source material included measurement of their grain size composition and a range of geochemical properties. Grain size composition was measured by laser diffraction after removal of the organic fraction, and chemical (sodium metaphosphate) and physical (ultrasonic) dispersion. Total concentrations of P, K, Ca, Na, Mg, Cu, Zn, Fe and Mn were measured by atomic absorption spectrometry after digestion with sulphuric acid (Tedesco, 1995). Total organic C was measured by the Walkley-Black method (Tedesco, 1995). Fe and Mn oxides were measured by atomic absorption spectrometry after extraction with Dithionite–Citrate–Sodium Bicarbonate (Inda Junior, 2002); and Fe and Mn oxides by extraction with ammonium acid oxalate (Inda Junior, 2002).

## Source discrimination

A key requirement of any sediment source fingerprinting exercise is the need to use statistical tests to identify a composite fingerprint or set of source material properties that is capable of discriminating between the potential sources. In this study, a variant of the two stage procedure advocated by Collins and Walling (2002) and Walling (2005) was used. In the first stage, the H test or Kruskall–Wallis non-parametric test (see Levin, 1999) is used to identify those fingerprint properties which were able to discriminate between the three potential sources, by testing the null hypothesis that the source material samples are drawn from the same population. The test is based on the following equation:

$$H_{\mathrm{calc}} = \frac{12}{N(N+1)}\left(\sum_{s=1}^{n}\frac{R_s^2}{n_l}\right) - 3(N+1) \qquad (1)$$

where $R_s$ is the sum of the *ranks* in source $s$; $n_l$ the number of the samples from source $s$; $N$ the sum of all $n_l$; and $n$ is the number of sources.

The $H$ values can be related to the sampling distribution of chi-square with $k-1$ degree freedom. Therefore, $H$ values were compared with chi-square values ($H$ critical). When $H_{\mathrm{calculated}} > H_{\mathrm{critical}}$, the null hypothesis is rejected and the variable is classified as being capable of discriminating between the sources. Each variable represents a geochemical property and the Kruskall–Wallis test was run for each property.

In the second stage, a stepwise multivariate discriminant function analysis is undertaken, in order to select the optimum sub-set of fingerprint properties from those identified as potential properties in the first stage. This analysis aims to maximise the discrimination between the sources, whilst minimizing the size of the optimum sub-set of properties. The STATISTICA® software package was used to execute the stepwise variable selection procedure. The procedure is based on minimizing Wilks' Lambda:

$$\Lambda^* = |\mathrm{SS}_{\mathrm{error}}|/|\mathrm{SS}_{\mathrm{error}} + \mathrm{SS}_{\mathrm{treat}}| \qquad (2)$$

where $\mathrm{SS}_{\mathrm{error}}$ is the matrix of the sum of squares and cross-products of the residuals component; and $\mathrm{SS}_{\mathrm{treat}}$ is the matrix of the sum of squares and cross-products of the treatment component. At each step, the variable that causes the greatest reduction in the overall Wilks' Lambda is selected. The Mahalanobis distance, a measure of distance between two points in the space defined by two or more correlated variables, was also used as auxiliary information to evaluate the capacity of the set of property variables to discriminate between the source groups. The Mahalanobis distance is similar to the Euclidean distance measure; except that it takes account the correlations between variables. Furthermore, this value provides an estimate of the variability of the fingerprint properties associated with each sample, based on its distance from the central point of the group. This measure was therefore used to establish the uncertainties associated with the fingerprint property values used to characterise each source.

## Source apportionment

The final element of the source fingerprinting exercise involves estimating the relative contribution of each potential source to the suspended sediment samples collected at the catchment outlet, by comparing the fingerprint of the sediment with those of the potential sources. This is achieved by using a multivariate mixing model:

$$y_i = \sum a_{is} P_s \quad (s = 1, 2, \ldots, n) \text{ and } (i = 1, 2, \ldots, m) \tag{3}$$

where $y_i$ is the concentration of the element $i$ in the suspended sediment sample, $a_{is}$ is the concentration of the element $i$ in source $s$; $P_s$ is the relative contribution of source $s$ (regression coefficients to be calculated by the model). The model assumes that the suspended sediment retains the characteristics of its source, and that the suspended sediment comprises material only from the identified sources, and the result is conditioned by two restrictions viz.

(i) $\sum P_s = 1$; and (4)

(ii) $0 < P_s < 1$ (5)

Examples of applying such mixing models are described by Yu and Oldfield (1989), Walling and Woodward (1995), Collins et al. (1997), Walling et al. (1999) and Walling and Collins (2000). Since the model is overdetermined (the number of equations is more than the number of unknown variables), it must be fitted iteratively by minimizing an objective function. In this study, the objective function was based on the sum of squares of the deviations of the predicted property concentrations from the measured values:

$$\sum_{i=1}^{m} \left\{ \left( y_i - \left( \sum_{s=1}^{n} P_s a_{is} Z_s \right) \right) \Big/ y_i \right\}^2 \tag{6}$$

where $y_i$ is the concentration of tracer property $i$ in the suspended sediment sample; $a_{is}$ the concentration of tracer property $i$ for source group $s$; $P_s$ the relative contribution from source $s$ (unknown variable to be determined by the model); and $Z_s$ is a particle size correction factor (see He and Walling, 1996). The particle size correction factor $Z_s$ is required to take account of differences in particle size composition between the suspended sediment and the source material, since it is well known that particle size exerts an important influence on the geochemical properties of fine sediment (e.g. Horowitz, 1991). An error assessment of the sediment mixing model was performed using the relative mean error (RME). This involves a comparison of the actual fingerprint property concentrations measured in a given suspended sediment sample with the corresponding values predicted by the model, based on the optimised percentage contribution from each source group. In this study, relative errors of <17% indicate that the optimised mixing model is able to provide an acceptable prediction of the fingerprint property concentrations associated with suspended sediment samples.

The mixing model was run using Matlab® software and the results are expressed as percentages, which represent the relative contributions of each source to the suspended sediment sample. It is important to recognise that such values of relative contribution will need to be combined with an estimate of the total mass of sediment transported by an event, in order to provide information on the absolute contribution from a given source. Where several suspended sediment samples are collected during an event, the relative contribution of the different sources to the total sediment yield for the event was estimated by weighting the relative contributions obtained for the individual samples according to the magnitude of the load at the time of sampling (Walling and Collins, 2000):

$$P_{sw} = \sum_{s=1}^{n} P_{sx} \left( \frac{L_x}{L_t} \right) \tag{7}$$

where $P_{sw}$ is the load-weighted percentage contribution from source grouping ($s$); $L_x$ the sediment load at the time sample ($x$) was collected; $L_t$ the sum of the sediment loads for the samples collected during the event; and $P_{sx}$ is the relative contribution from source grouping ($s$) to sediment sample ($x$). A similar procedure was used to calculate the load-weighted mean contributions from the different sources for the pre- and post-treatment periods. In this case the source contributions associated with the individual events were weighted according to the total sediment yields associated with those events.

## Results

As indicated above, the study undertaken in the Arvorezinha catchment was designed to assess the impact of improved land management on sediment mobilisation and delivery. The study was based on a traditional single catchment experiment. The response of the catchment under the original land management was compared with that under improved land management, by establishing event-based relationships between runoff and rainfall and between the sediment response of those events and both rainfall and runoff, and assessing the changes in these relationships after the introduction of improved land management. Sediment source tracing or fingerprinting investigations were incorporated into the study, in order to provide further information on changes in the sediment dynamics of the catchment resulting from improved land management.

When undertaking a catchment experiment of this nature, there is ideally a need to monitor the response of the catchment for an extended period of time prior to introducing changed management practices. The initial period of monitoring is required to 'calibrate' the catchment. In practice, however, long calibration periods are frequently not available, since such studies are often undertaken in response to an impending change in land use or land management and only a short period is available for calibration. This was the situation in the present study, where it was possible to monitor the catchment for only 1 year prior to the introduction of improved land management. The short duration of the calibration period was, however, to some extent overcome by focussing on the response of the catchment during individual storm events, rather than on aggregate measures of annual response, such as annual sediment yield or mean suspended sediment concentration. It is, nevertheless, important to ensure that the calibration period provided a representative range of events in order to generate meaningful calibration relationships. Equally, it is important that the period following the change in management practices should include a wide range of storm events, in order to provide a comprehensive assessment of the impact of that change. Table 1 summarises the water discharge and rainfall records for the period 2002–2006, with the year being divided into three 4-month periods. These data indicate that, when compared to the longer-term mean

**Table 1** A summary of precipitation and flow conditions in the Arvorezinha catchment during the study period

| Period | 2002–2003 | 2003–2004 | 2004–2005 | 2005–2006 |
|---|---|---|---|---|
| *Precipitation (mm)* | | | | |
| April–July | 895 | 673 | 595 | 797 |
| August–November | 905 | 458 | 509 | 717 |
| December–March | 650 | 519 | 310 | 415 |
| Total | 2450 | 1650 | 1414 | 1929 |
| *Average flow (l $s^{-1}$)* | | | | |
| April–July | 47.76 | 38.19 | 22.94 | 39.03 |
| August–November | 67.81 | 17.58 | 29.68 | 43.13 |
| December–March | 24.90 | 15.10 | 4.37 | 7.05 |
| Average | 46.82 | 23.62 | 19.00 | 29.74 |

annual rainfall (1605 mm), two of the study years (2002–2003 and 2005–2006) were wetter than the average, that one year (2003–2004) was close to the average and that one year (2004–2005) was drier than the average, although there were significant storm events in all seasons. The fact that the initial observation year (2002–2003) was wetter than normal inevitably raises some uncertainty as to the representativeness of the calibration data available for this year. However, a wide range of storm events of varying magnitude occurred during the year and these are seen as providing a meaningful basis for calibrating the runoff and sediment response of the study catchment whilst under traditional land management.

The limitations of the period of record available for the study, which relate to both its shortness and the inter-annual variability of rainfall, necessarily introduce some uncertainty into a rigorous analysis of the changes in catchment response resulting from changing land management practice and some caution is required in interpreting the results obtained from the traditional monitoring approach. However, the primary purpose of this contribution is to demonstrate the potential for using sediment source tracing techniques to complement and extend the results provided by traditional monitoring and the available record provides an effective basis for achieving this objective. Analysis has focussed on the suite of 19 storm runoff events monitored prior to August 2003, that are seen as representing the land management prior to its change to minimum-till, the six events that occurred between October 2003 and February 2004 that are representative of the transition phase and the 25 events associated with the subsequent period of improved land management. The event that occurred on October 25, 2003, at the beginning of the transition phase, resulted from a total storm-period rainfall of nearly 150 mm, and must be viewed as an extreme event when compared to the remaining 49 events, for which the maximum rainfall was 100 mm. The occurrence of this extreme event at the beginning of the transition phase must again be seen as an undesirable feature of the available record, since the possibility that it caused changes in the subsequent behaviour of the study catchment must be recognised.

## Changes in runoff response

Any change in storm runoff response associated with the change in land management that occurred in the Arvorezinha catchment after October 2003 might be expected to exert a key influence on changes in the storm-period sediment response and attention is, therefore, initially directed to an analysis of both peak discharges and storm runoff volume associated with individual events. In this context, the peak discharge associated with an individual storm event was defined as the increase in discharge above the discharge preceding the event and the storm runoff volume was calculated using a hydrograph separation procedure employing a semi-logarithmic plot to identify the inflection point on the falling limb of the hydrograph.

Fig. 3 presents relationships between peak discharge and storm runoff volume and two storm rainfall parameters for two periods, representing the pre-treatment period and post-treatment period, which also includes the transition year 2003–2004. Storm rainfall has been represented by the total storm rainfall associated with the runoff event $P$ (mm) and a storm rainfall index $P_{\text{index}}$ (mm) that incorporates both this rainfall and the influence of rainfall during the previous 2 days. This rainfall index was calculated using:

$$P_{\text{index}} = 0.777 * P_1 + 0.189 * P_2 + 0.034 * P_3 \tag{8}$$

where $P_1$ is the storm rainfall associated with the event, $P_2$ the rainfall during the 24 h prior to the event, and $P_3$ is the rainfall recorded between 24 and 48 h prior to the event. The weighting coefficients applied to the three rainfall total were derived via a multiple regression analysis relating storm runoff volume to the three rainfall totals as independent variables and using the regression coefficients as the weighting coefficients. This analysis was undertaken on the data for the storm events occurring prior to October 2003.

In the plots presented in Fig. 3, all the data relating to the post October 2003 period have been used to derive the relationships for the post-treatment period, but the data points associated with the period October 2003 to February 2004 have been distinguished on the plot as belonging to the transition period. A substantial proportion of the catchment was influenced by improved management practices at this time, but the proportion was not as great as in the main post-treatment period. The relationships defined by the data from the pre- and post-treatment periods have been represented by a power function and the $r^2$ values for these relationships are reported in Fig. 3. All the relationships showed significant (>95%) differences between

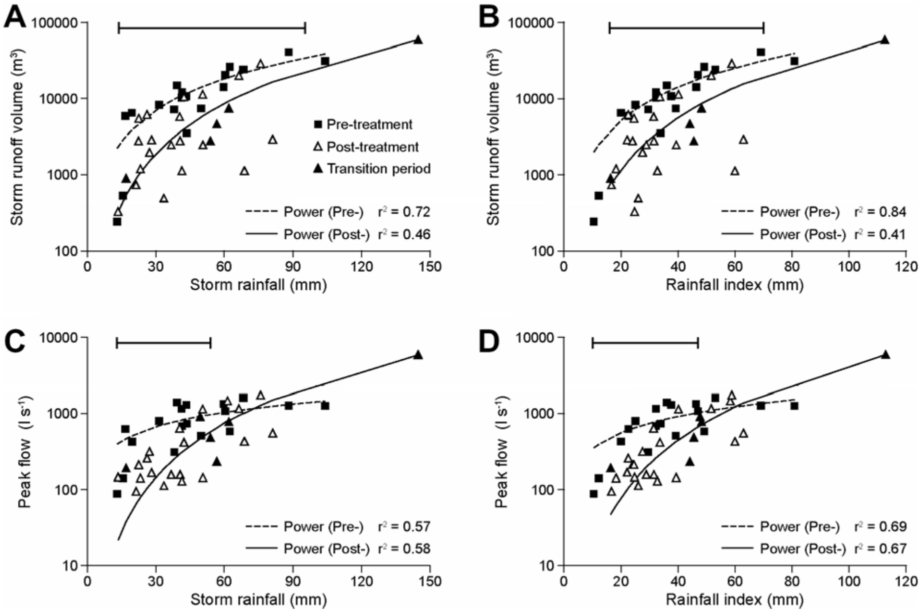


**Figure 3** Relationships between peak discharge and storm runoff volume and storm rainfall amount and the rainfall index for individual storm hydrographs occurring during the pre- and post-treatment periods. The data points relating to the transition period within the post-treatment period have been distinguished. The bar above the graphs identifies the range of the independent variable over which the relationships represented by the curves are significantly different at the >95% level of confidence (see Fig. 4).

the pre- and post-treatment periods, over at least part of the range of the storm rainfall or rainfall index, and this range has been indicated above the plots with a bar. Fig. 4 provides an example of how these bars were defined. The 95% confidence intervals for the individual regression relationships have been computed (eg. Sahai and Thompson, 1974) and the relationships are assumed to be significantly different when the confidence intervals around the curves do not overlap.

All four plots in Fig. 3 provide evidence that both storm runoff volumes (Fig. 3A and B) and storm hydrograph peaks (Fig. 3C and D), associated with a given amount of storm rainfall, have decreased after October 2003. The storm runoff response of the catchment during the transition period appears to show no difference from that of the main post-treatment period. Storm runoff volumes show a significant decrease between the pre- and post-treatment periods over most of the rainfall range, with values showing an average decrease of ca. 60% for lower magnitude rainfall events and of about 20% for higher magnitude events. In the case of storm hydrograph peaks, the pre- and post-treatment relationships are only significantly different for events with low and intermediate magnitude rainfall, with peak discharges declining by about 50% for lower magnitude events and 30% for events of intermediate magnitude. The data plots suggest that the decrease in both storm runoff volume and peak flow reduces markedly for high values of $P$ and $P_{\text{index}}$. The reduced impact of improved land management on storm runoff volumes, and particularly on peak discharges, for high magnitude storm events conforms to physical reasoning, in that the effects of improved land management are likely to be less clear for high magnitude rainfall events, when rainfall intensities will commonly be high and the soils approach saturation.

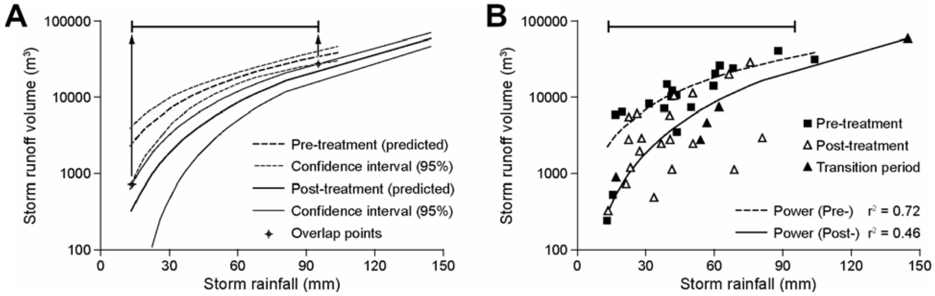


**Figure 4** An example to show how the range of the independent variable, over which the curves representing the relationships for the pre- and post-treatment periods can be treated as different at the >95% level, was established. In (A) the 95% confidence limits for the two relationships have been plotted and the range of the independent variable over which the confidence limits do not overlap has been established. In (B) this range has been marked on the plot showing the data for the two periods and the two relationships fitted to those data.

## Changes in sediment response

In analysing the change in sediment response associated with the change in land management, attention has focussed on both the suspended sediment yield ($t$) of individual events and the maximum and flow-weighted mean concentration (mg $l^{-1}$) associated with those events. Fig. 5 presents relationships between these variables and $P_{\text{index}}$ and an estimate of the erosivity of the rainfall for an individual event. Emphasis is placed on the use of rainfall variables as independent variables, since the results presented in Fig. 3 demonstrate that the changing catchment management has influenced the runoff response of the catchment. The rainfall input can be viewed as independent of those changes and contrasts between the pre- and post-treatment relationships can be used to assess the impact of changing land management on the sediment response. $P_{\text{index}}$ rather than $P$, was used as the measure of storm rainfall, since Fig. 3 indicates that it is generally a better predictor of both peak discharge and storm runoff volume. The measure of storm rainfall erosivity for individual events $EI_{30}$ (MJ mm ha$^{-1}$ h$^{-1}$) represents the product of the estimate of the total kinetic energy for an event and the maximum 30-min rainfall intensity during the event. This was estimated by applying the relationship between erosivity and rainfall intensity developed by Castro Filho et al. (1982) for the state of Paraná, in southern Brazil, where climatic conditions are similar to those in the study area, to the rainfall records for the individual events, which are based on a 10 min time increment:

$$EI_{30} = [28.814 + (10.800 + 7.896 \log I_{30})P]I_{30} \cdot 10^{-3} \quad (9)$$

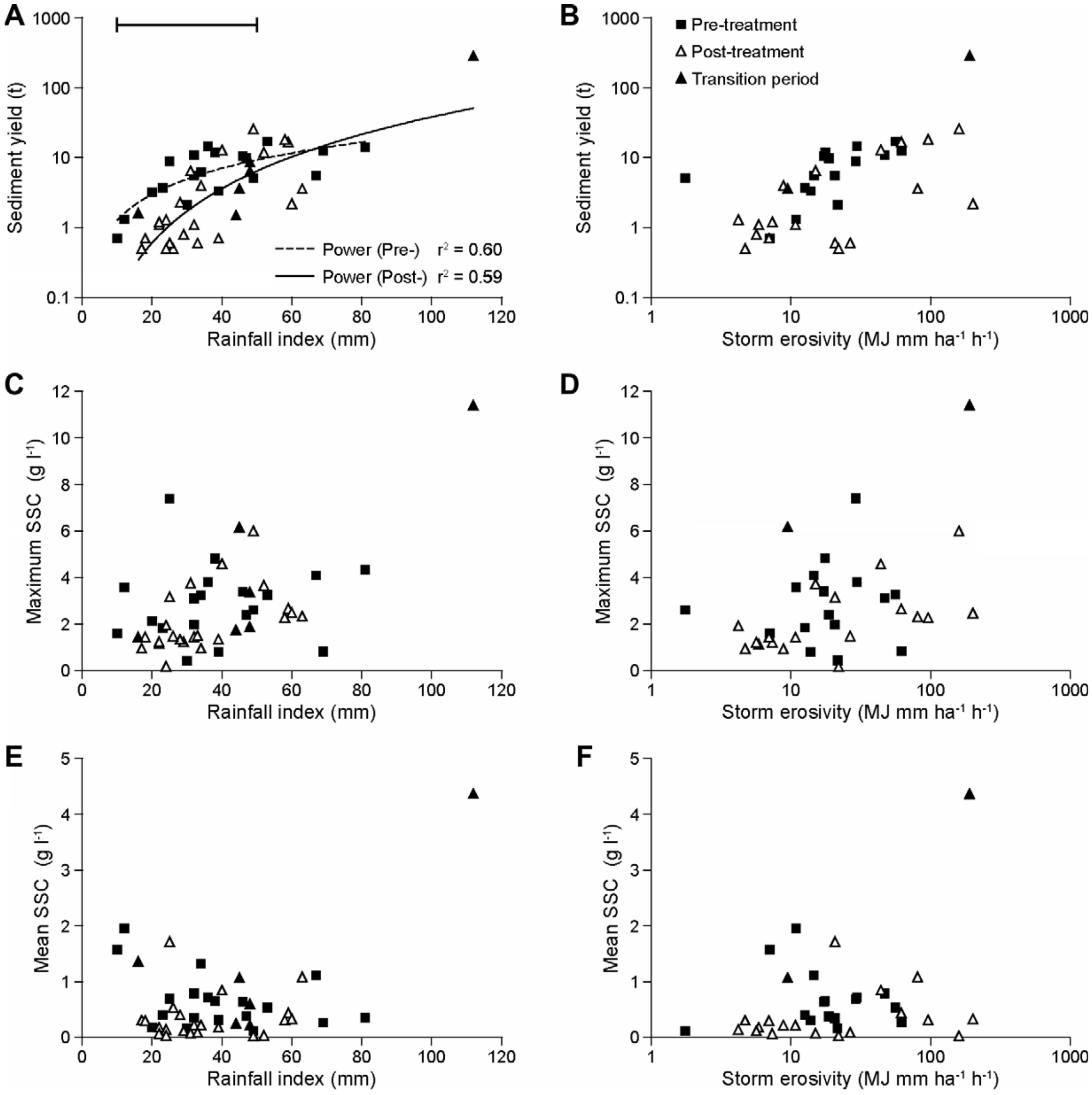


**Figure 5** Relationships between event suspended sediment yield and maximum and mean storm-period suspended sediment concentration and storm precipitation and erosivity, for the pre- and post-treatment periods. Only those numerical relationships significant at >95% have been plotted.

where $I_{30}$ is the maximum 30-min rainfall intensity (mm h$^{-1}$), and $P$ (mm) is the storm rainfall associated with the event.

In the absence of local information on the relationship between the drop size distribution and rainfall intensity, this relationship provides an approximate estimate of rainfall energy. As with Fig. 3, the data for the pre- and post-treatment periods have been shown separately and the data for the transitional phase, which are included within the post-treatment period, have also been distinguished. Again, only those relationships for the pre- and post-treatment periods that are statistically significant (>95%) have been plotted, and the bar delimits the range over which the relationships for two periods are significantly different. In this context, only the relationships between event sediment yield and the precipitation index (Fig. 5A) are seen to be statistically significant.

Fig. 5A provides evidence that the change in land management caused a significant reduction in sediment yield, with the fitted relationship suggesting reductions of as much as 80% for low magnitude rainfall events and of ca. 40% for events of intermediate magnitude. However, as with the relationships for peak flow presented in Fig. 3, the magnitude of this reduction appears to be reduced for high magnitude events and no decrease is apparent for higher magnitude storm events. The relationships fitted to the data plotted in Fig. 5B are not statistically significant at the 95% level, but the data again provide some evidence of a reduction in sediment yield during the post-treatment period. The pre- and post-treatment relationships for event maximum and flow-weighted mean suspended sediment concentrations presented in Fig. 5C–F, respectively, provide no clear evidence of a change between the two periods, although there is, nevertheless, some tendency for concentrations for a given value of $P_{\text{index}}$ or $EI_{30}$ to decrease. The lack of a clear shift in the relationships between the measures of storm-period suspended sediment concentration and precipitation amount and erosivity for the pre- and post-treatment periods indicates that the reduction in sediment yield apparent for the post-treatment period in Fig. 5A is primarily a result of the reduced volume of storm runoff, rather than reduced sediment concentrations.

## Sediment source fingerprinting

### Source discrimination

The results of the two-stage statistical analysis provided clear confirmation that it was possible to use a composite fingerprint, comprising a number of sediment properties, to discriminate the three potential sediment sources in the study catchment. Table 2 presents the results of applying the Kruskall–Wallis test to the source material samples and shows that 10 properties showed a statistically significant difference between the sources at the 90% level ($H_{\text{critical}} = 4.61$).

The 10 properties identified by the Kruskall–Wallis test as providing statistically significant discrimination between the three sets of source material samples were then entered into the stepwise multivariate discriminant function analysis, in order to select the optimum set for maximising discrimination, whilst minimising dimensionality. The set selected comprised eight properties (Table 3). The final value of the Wilks' Lambda parameter was 0.071, which represents a nearly 100% discrimination between the three sources ($F_{\text{calculated}} = 11.217$ and $F_{\text{critical}} = 1.870$). Table 3 shows the progressive change of the Wilks' Lambda value as the variables are introduced into the analysis. The variables $Fe_t$ and $Fe_{\text{oxa}}$ and $Mn_t$ and $Mn_{\text{oxa}}$ are strongly intercorrelated ($r^2 > 0.70$) and, as a result, $Mn_{\text{oxa}}$ and $Fe_{\text{oxa}}$ were excluded by the stepwise analysis.

Consideration of the Mahalanobis distance values (Table 4) shows that the stream channel and field source groups are the most similar in terms of their composite fingerprints; and that the unpaved roads are closer to the stream channel source group. The distances between all sources are significantly different, although the scatter of the points within each group introduces a source of uncertainty. Table 5 shows the percent of samples that are correctly classified for each source. All samples from crop fields and unpaved roads were classified correctly, but 10% of the samples from

**Table 2** Use of the Kruskall–Wallis *H* test to test source discrimination

| | P | $Mn_{\text{oxa}}$ | K | $Mn_t$ | $Fe_t$ | $Fe_{\text{oxa}}$ | Ca |
|---|---|---|---|---|---|---|---|
| *H* | 29.00 | 20.26 | 19.56 | 15.97 | 14.55 | 14.22 | 13.40 |
| *P* | <0.0001 | <0.0001 | 0.0001 | 0.0003 | 0.0007 | 0.0007 | 0.001 |

| | Na | Cu | Zn | Mg | $Fe_{\text{dit}}$ | $Mn_{\text{dit}}$ |
|---|---|---|---|---|---|---|
| *H* | 13.26 | 10.92 | 4.84 | 3.46 | 1.25 | 0.88 |
| *P* | 0.0010 | 0.0040 | 0.0800 | 0.1700 | 0.5300 | 0.6400 |

*t*: total concentration; dit: concentration associated with pedogenic oxide; and oxa: concentration associated with non-pedogenic oxide.

**Table 3** Results of the stepwise discriminant function analysis as indicated by the Wilks' Lambda values

| | P | Ca | K | $Mn_t$ | Cu | Na | Zn | $Fe_t$ |
|---|---|---|---|---|---|---|---|---|
| Number of variables in model: 8; Grouping: 3 groups | | | | | | | | |
| Cumulative Wilks' Lambda: | | | | | | | | |
| $\Lambda^*$ | 0.251 | 0.220 | 0.194 | 0.147 | 0.089 | 0.078 | 0.072 | 0.071 |

**Table 4** Results of the discriminant function analysis: Mahalanobis distance values

| Squared Mahalanobis distances | | | $F(0.05)$-values; df = 7;30 $F_{\text{critical}} = 2.33$ | | |
|---|---|---|---|---|---|
| | Stream channels | Unpaved roads | | Stream channels | Unpaved roads |
| Unpaved roads | 14.2 | – | Unpaved roads | 7.16 | – |
| Crop fields | 11.6 | 40.0 | Crop fields | 8.41 | 22.57 |

**Table 5** Results of the error analysis associated with the variability within of each source

| Crop fields | Stream channels | Unpaved roads |
|---|---|---|
| *Percentage of samples of each source classified correctly in its own group* | | |
| 100% | 90% | 100% |
| *Uncertainty associated with the discrimination of the source* | | |
| 5.61% | 15.2% | 5.06% |

stream channels were classified as belonging to unpaved roads. Even when a sample is classified correctly, it is important to consider the distance to the group central point (i.e. the scatter within the group). The last line in Table 5 combines the errors associated with: (i) distance between the groups, (ii) the percent of samples incorrectly classified, and (iii) the scatter within the group. These values provide a useful measure of the uncertainty associated with each source. However, further work is required to investigate the propagation of this uncertainty within the classification model and to refine the use of the Mahalanobis distance as a measure of uncertainty.

Considering further the properties used to discriminate the three potential sediment sources, it can be seen that several of these will be sensitive to agricultural practices and thus the basic distinction between cultivated soil from the fields and channel bank material and surface material from unpaved roads, which can both be expected to be more similar to uncultivated soil and subsoil. The application of fertiliser and manure to the cultivated fields results in high P and K concentrations in source material from cultivated fields, lower values in channel bank material and even lower values in material from the surface of the unpaved roads, which cut into the subsoil. Most of the P and K present in the sediment transported by the stream are closely associated with clay minerals and these properties can be assumed to provide an essentially conservative tracer. Like P and K, Ca and Na concentrations are also responsive to land use activities in the catchment. Calcium is applied to the cultivated fields as lime, to regulate the pH, and sodium accumulates in poorly managed soils. Manganese preferentially accumulates in saturated areas and is therefore useful for discriminating sediment mobilised from channel banks. Fe, Zn and Cu concentrations were also found to exhibit significant contrasts between the three source groups and therefore provide good source tracers, particularly in view of their conservative behaviour.

### Source apportionment

Since both the source material and suspended sediment samples had been sieved to <150 μm and further comparisons indicated that there was little difference between the particle size composition of the <150 μm fractions of the source material and suspended sediment samples, the mixing model presented in Eq. (3) was applied to the individual events without further correction for grain size contrasts between the source material and suspended sediment samples. Where more than one suspended sediment sample had been collected during an event, the load-weighted mean source contribution for the event was calculated (see Eq. (7)). The relatively low values of relative mean error (RME) obtained when applying the mixing model to the data for the individual events confirm that the optimisation routine provided an efficient means of minimizing the objective function. However, for a few events the RME value was in excess of 17%, the value set as the threshold for acceptance of the results and these results were excluded from further analysis. For a few events where the RME threshold was exceeded by a small margin and this was caused by only one or two fingerprint properties, the source apportionment results were retained. The final results of the source apportionment are presented in Table 6. Table 6 provides estimates of the relative contributions of the three sediment sources to the sediment yield of the individual sampled events and an estimate of the load-weighted mean contributions (LWM) from the three sources for both the pre- and the post-treatment periods. Two estimates of the load-weighted mean contributions from the three sources have been presented for the post-treatment period. One of these excludes the extreme event of October 25, 2003, since it has been shown above that the impact of improved management is likely to be less evident for high magnitude events and the inclusion of this event therefore reduces the apparent impact of the improved land management.

### Changes in the relative contributions from the individual source groups in response to changes in land management

The results presented in Table 6 indicate that the introduction of improved land management practices in the study catchment resulted in a significant change in the relative importance of the three main source groups. A comparison of the load-weighted mean contributions for the pre- and post-treatment periods (excluding the extreme event of October 25, 2003) indicates that the contribution from the fields under crops and the unpaved roads decreased from 63% and 36% to 54% and 24%, respectively, whereas the contribution from the river channels increased from 2% to 22%. The changes in the relative contributions from the three source groups consequent upon the change in land management are considered further in Fig. 6, where the results for the individual events have been plotted on a trilinear graph, similar to that used for soil textural classification. Fig. 6

**Table 6** Relative contribution of the three sediment source groups to the sediment yield of individual sampled events

| Pre-treatment | Relative sediment yield (%) | | | RME[a] | Post-treatment | Relative sediment yield (%) | | | RME[a] |
|---|---|---|---|---|---|---|---|---|---|
| | Stream channels | Unpaved roads | Crop fields | | | Stream channels | Unpaved roads | Crop fields | |
| 15/05/02 | 4 | 19 | 77 | 7.8 | 25/10/03 | 12 | 8 | 80 | 6.2 |
| 20/05/02 | 2 | 43 | 55 | 7.2 | 11/12/03 | 16 | 30 | 54 | 5.2 |
| 13/06/02 | 3 | 3 | 93 | 5.7 | 15/12/03 | 30 | 29 | 41 | 11.6 |
| 01/07/02 | 0 | 43 | 57 | 5.6 | 30/12/03 | 23 | 40 | 37 | 10.4 |
| 20/08/02 | 1 | 35 | 63 | 8.3 | 10/01/04 | 19 | 40 | 41 | 4.9 |
| 22/08/02 | 2 | 35 | 63 | 8.4 | 05/02/04 | 32 | 24 | 44 | 9.4 |
| 12/09/02 | 1 | 49 | 51 | 13.3 | 07/05/04 | 22 | 2 | 76 | 12.1 |
| 25/10/02 | 1 | 37 | 62 | 6.5 | 25/05/04 | 11 | 24 | 64 | 10.7 |
| 18/11/02 | 0 | 57 | 43 | 14.3 | 10/06/04 | 10 | 21 | 69 | 7.9 |
| 20/11/02 | 0 | 57 | 43 | 16.8 | 01/07/04 | 29 | 7 | 64 | 11.8 |
| 01/12/02 | 1 | 59 | 40 | 15.9 | 07/07/04 | 5 | 41 | 54 | 16.4 |
| 06/12/02 | 1 | 45 | 54 | 12.8 | 15/07/04 | 12 | 17 | 71 | 14.3 |
| 25/04/03 | 1 | 33 | 67 | 13.8 | 20/09/04 | 2 | 36 | 63 | 17.1 |
| 29/04/03 | 5 | 2 | 94 | 12.9 | 21/09/04[b] | 0 | 92 | 8 | 27.5 |
| 11/06/03 | 2 | 61 | 37 | 15.2 | 22/09/04 | 10 | 13 | 78 | 8.9 |
| 14/06/03 | 3 | 28 | 69 | 11.4 | 13/10/04 | 29 | 31 | 40 | 7.2 |
| 08/07/03 | 1 | 31 | 68 | 11.6 | 16/10/04 | 1 | 35 | 64 | 15.2 |
| 15/07/03 | 3 | 31 | 66 | 12.8 | 23/10/04 | 44 | 38 | 19 | 8.2 |
| 22/07/03 | 1 | 41 | 58 | 17.1 | 25/10/04[b] | 0 | 92 | 8 | 27.6 |
| | | | | | 09/11/04 | 10 | 14 | 76 | 8.7 |
| | | | | | 11/11/04 | 10 | 32 | 58 | 11.3 |
| | | | | | 09/01/05 | 10 | 50 | 40 | 4.4 |
| | | | | | 13/03/05 | 30 | 31 | 39 | 13.5 |
| | | | | | 11/05/05 | 25 | 3 | 72 | 9.7 |
| | | | | | 18/05/05 | 8 | 34 | 59 | 8.0 |
| | | | | | 17/06/05 | 1 | 90 | 9 | 11.1 |
| | | | | | 21/07/05 | 28 | 32 | 40 | 9.1 |
| | | | | | 04/10/05 | 34 | 19 | 47 | 10.0 |
| | | | | | 27/10/05 | 31 | 24 | 45 | 10.1 |
| | | | | | 23/12/05 | 18 | 41 | 41 | 11.1 |
| | | | | | 19/03/06 | 21 | 36 | 43 | 12.1 |
| Minimum | 0 | 2 | 37 | 5.6 | Minimum | 1 | 2 | 9 | 4.4 |
| Maximum | 5 | 61 | 94 | 17.1 | Maximum | 44 | 90 | 80 | 17.1 |
| Mean | 2 | 37 | 61 | 11.4 | Mean | 18 | 29 | 53 | 10.3 |
| Weighted mean (%) | 2 | 36 | 63 | | Weighted mean (%) | 15 | 13 | 72 | |
| | | | | | Weighted mean (%)[c] | 22 | 24 | 54 | |

RME — relative mean error (%).

[a] Where more than one sample was collected during an event the RME value listed is the mean for the samples collected during the event.

[b] Events excluded from the analysis (RME > 17%).

[c] Load-weighted mean excluding the event of October 25, 2003.

confirms that the pre- and post-treatment periods are associated with contrasting source contributions, which plot as separate fields on the tri-linear plot. The results for the six events occurring between October 2003 and February 2004, which have previously been classified as transitional are again distinguished in Fig. 6. However, these values plot clearly within the field associated with the post-treatment data and, as concluded previously, can be grouped with these data. The greatest contrast between the pre- and post-treatment periods is found in the contribution of stream channels. During the pre-treatment period, the channel contribution was very low ranging from 0% to 5%. However, after the change in land management the channel contribution generally showed a marked increase and ranged between 1% and 44%. The mean contribution from unpaved roads decreased during the post-treatment period from 37% to 29%, although the range of the contributions associated with individual storms increased from 2–61% to 2–90%. In contrast, and as expected, the increase in the relative importance of channel was balanced by a reduction in the relative contribution from crop fields, with the range of this contribution declining from 37–94% to 9–80%.

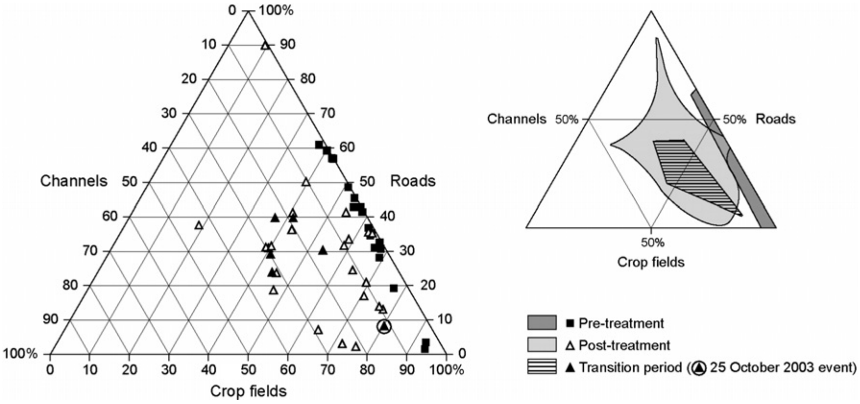


**Figure 6** The relative contribution of the three source groups to the sediment yields of the individual events monitored during the pre- and post-treatment periods.

It is important to recognise that the values presented above relate to *relative* contributions and that their further interpretation must be coupled with information on changes in the absolute magnitude of the sediment yields of individual events, such as presented in Fig. 5 above. Thus, although the relative contribution (%) from a particular source might increase during the post-treatment period, its absolute magnitude (*t*) might decrease in line with the overall reduction in sediment yields during the post-treatment period. In general terms, however, the reduction in the relative importance of crop fields and unpaved roads as sediment sources is consistent with the adoption of minimum-till practices and thus reduced surface runoff and reduced erosion and sediment mobilisation from the fields. The increased importance of stream channels could simply reflect the reduced importance of the other two sources, rather than the direct impact of improved land management. However, channel erosion, and thus the contribution from stream channels, might be expected to increase in response to reduced sediment input to the channel and thus increased transport capacity. Further elucidation of the changes in the sediment response of the study catchment must also consider changes in the absolute amounts of sediment contributed by the individual sources.

## The impact of changing land management on sediment mobilisation within the study catchment

By combining the information on the relative contribution of the three source groups to the sediment yields of individual events listed in Table 6 with the values of sediment yield available for those events, it is possible to calculate the amounts of sediment mobilised from the three source groups during those events. Furthermore, by comparing pre- and post-treatment relationships between these values and variables representing the runoff and precipitation associated with the events, it is possible to identify changes in the amounts of sediment mobilised from the individual sources and to relate these to the changes in land management that have occurred within the catchment. The relationships are presented in Fig. 7. Again, the data points associated with the transition phase of the post-treatment period have been distinguished and only the significant relationships have been plotted.

Fig. 7 provides clear evidence that sediment mobilisation from the stream channel during individual events has increased substantially after the introduction of improved land management in the study catchment. The relationship between the amount of sediment mobilised from stream channels and peak flow presented in Fig. 7G indicates that sediment mobilisation from stream channels for a given peak flow could be as much as an order of magnitude greater in the post-treatment period. Even though the peak discharges generated by a given storm are shown by Fig. 3 to have decreased in the post-treatment period, the increase in sediment mobilisation from stream channels by a storm event of a given magnitude is clearly much greater during the post-treatment period than in the pre-treatment period. This situation is further confirmed by Fig. 7H, which presents the relationships between the amount of sediment mobilised from stream channels and rainfall input ($P_{\text{index}}$), and therefore removes the need to consider the changes in peak discharge associated with the introduction of improved land management practices. The plot for this relationship provides further evidence that the amount of sediment mobilised from stream channels by a rainfall event of a given magnitude increased greatly in the post-treatment period. Furthermore, both Fig. 7G and H show no evidence of the increased sediment mobilisation from stream channels associated with the post-treatment period reducing during high magnitude events. This contrasts with the response of the overall sediment yield discussed above, and the other two sediment sources, discussed below, where the increase is seen to reduce markedly, or even disappear, during high magnitude events.

As indicated above, the increase in sediment mobilisation from stream channels in the post-treatment period can be tentatively related to reduced erosion on the fields and thus reduced sediment inputs to the channel, resulting in an increased capacity of the flow to scour the channel. Field observations within the study catchment during the post-treatment period produced visual evidence of increased bed scour and bank collapse which confirms this interpretation. A small deepening of the channel associated with scour can result in increased instability of the channel banks and thus increased bank erosion. This evidence is also consistent with the lack of any reduction in the post-treatment increase in sediment mobilisation from stream

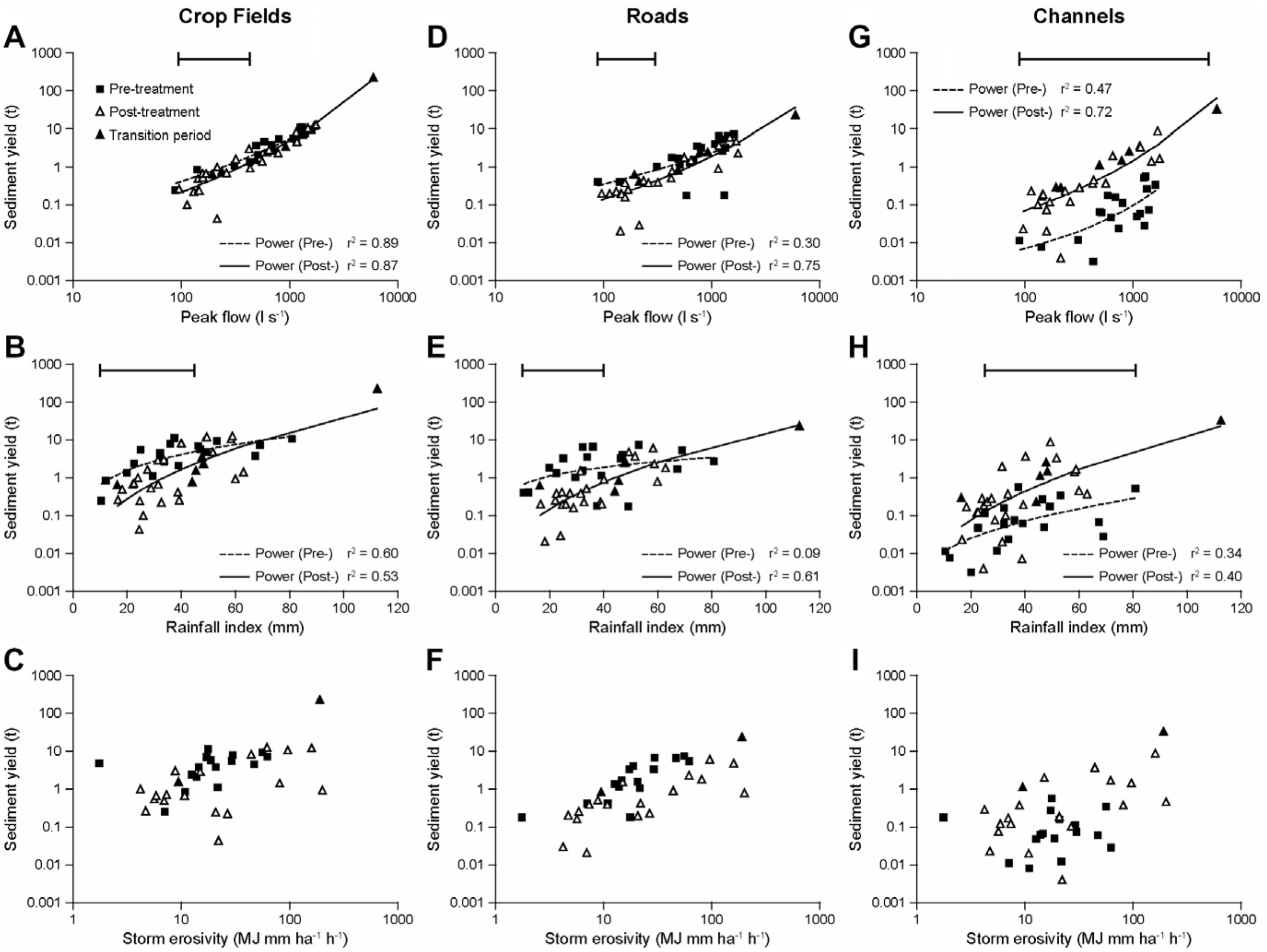


**Figure 7** Pre- and post-treatment relationships between the amount of sediment mobilised from the three source groups during a storm event and the peak flow and precipitation input associated with the event.

channels during high magnitude events, when scour and bank collapse are likely to be most effective. In the case of the unpaved roads, the data presented in Fig. 7D and E indicate that amounts of sediment contributed from this source decreased substantially in the post-treatment period for events of low and intermediate magnitude, although the decrease is substantially reduced, and even disappears, for high magnitude events. This situation is consistent with expectations and field observations, since the introduction of minimum-till practices should reduce surface runoff generation within the catchment and thus reduce the amount of runoff routed along unpaved roads, except during high magnitude events, for which Fig. 3 has shown that there is less difference in the amount of storm runoff generated between pre- and post-treatment conditions. Turning finally to the cultivated fields, Fig. 7A indicates that there is little difference in the pre- and post-treatment relationships between sediment generation from the fields and peak discharge; although there is some evidence that sediment mobilisation for low magnitude events decreases in the post-treatment period. This apparent lack of any impact from the change in land management reflects the fact that peak discharges for a given rainfall input were significantly reduced during the post-treatment period (see Fig. 3). In contrast, Fig. 7B demonstrates that the amounts of sediment mobilised from field sources for a given value of $P_{\text{index}}$ were significantly less for storms of low and intermediate magnitude during the post-treatment period. This reduction reflects the influence of the minimum-till management system in reducing surface runoff and increasing surface protection and surface roughness, thereby reducing sediment mobilisation. As discussed previously, the effects of improved management are less evident for high magnitude storm events.

## Discussion

The results presented above provide a useful demonstration of the potential for using sediment source tracing techniques to complement and extend the use of more traditional monitoring approaches to assessing the impact of improved land management in reducing soil erosion and sediment yields from small catchments. The traditional approach, based on monitoring water and sediment yield at the catchment outlet, indicated that the introduction of minimum-till practices in the Arvorezinha catchment resulted in reduced storm-period sediment yields, primarily for events of low and intermediate magnitude. For high magnitude events, the reduction in sediment yield was more limited. Inclusion of sediment source tracing techniques in the study provided important additional information on the changes in sediment response resulting from the introduction of improved land management and demonstrated that the net changes documented using traditional monitoring techniques comprised a more complex set of changes. The source tracing results confirmed the importance of three main sediment sources within the catchment, namely the fields under crops, the stream channels and unpaved roads and provided information on their relative contributions. They also demonstrated that the introduction of minimum-till practices within the Arvorezinha catchment caused erosion and sediment mobilisation from the crop fields and unpaved roads to decline, in line with the evidence provided by the traditional monitoring. However, they also demonstrated that sediment mobilisation from the channel system increased in the post-treatment period due to channel scour and bank collapse associated with reduced sediment inputs and increased transport capacity. The effects of improved land management in reducing soil erosion and sediment delivery from the crop fields and unpaved roads was therefore greater than suggested by the traditional techniques, which were unable to take account of the increased sediment mobilisation from stream channels during the post-treatment period.

As a means of generalising and summarising the results presented in Figs. 5 and 7, Table 7 presents generalised estimates of the changes in sediment yield associated with the shift from traditional to minimum till management in the Arvorezinha catchment, based on the pre- and post-treatment relationships, provided by the traditional monitoring (Fig. 5) and the sediment source tracing investigation (Fig. 7). Emphasis is placed on the relationships involving $P_{\text{index}}$ and the regression lines fitted to these plots (i.e. Figs. 5A and 7B, E and H), since these appear to provide a better fit to the available data. A low, an intermediate and a high magnitude event are considered and for simplicity in calculating the $P_{\text{index}}$ it is assumed that there had been no rain in the previous 2 days. The information presented in Table 7 emphasises the lesser impact of improved catchment management in reducing sediment yield during higher magnitude events and further highlights the improved understanding of the changes in sediment response associated with the shift from conventional to minimum-till provided by the source tracing work. Whilst sediment mobilisation from crop fields and unpaved roads is reduced during the post-treatment period, that from stream channels is increased. Furthermore, whereas the effectiveness of the improved management in decreasing sediment mobilisation from the crop fields and unpaved roads during the post-treatment period, decreases as storm magnitude increases, the increase in mobilisation from stream channels increases further for high magnitude events. This facet of the changing catchment response emphasises that any attempt to predict future changes in sediment yield from catchments, as a result of improved catchment management, should take account of the potential increase in sediment mobilisation from stream channels, as well as the reduction in erosion and sediment delivery from the crop fields and unpaved roads.

Although the results presented in Table 7 demonstrate that the introduction of improved land management within the Arvorezinha catchment has resulted in reduced sediment yields, Fig. 5 demonstrates that there is little evidence that the post-treatment period was associated with reduced suspended sediment concentrations. This in part reflects the increase in sediment mobilisation from stream channels that could offset any reduction in the sediment concentrations associated with runoff from the field areas. Thus, although the improved land management has succeeded in reducing the sediment yield from the Arvorezinha catchment, it has been much less successful in reducing suspended sediment concentrations and therefore the turbidity of the stream. The latter can be important in degrading aquatic habitats. It is also important to recognise that the changing sediment source contributions will change the geochemistry of the sediment. In this catchment the reduced contribution from the field areas and the increased contribution from stream channels has resulted in a reduction of

**Table 7** Generalised estimates of the impact of changing land management within the study catchment on storm-period sediment yields, based on the relationships presented in Figs. 5A and 7B, E and H

**(A) Traditional Monitoring**

| Rainfall Index (mm) | Total Sediment Yield (t) | | |
|---|---|---|---|
| | Pre-treatment | Post-treatment | Change |
| 15 | 2.039 | 0.335 | −84% |
| 30 | 4.882 | 2.023 | −59% |
| 60 | 11.689 | 12.197 | +4% |

**(B) Traditional Monitoring plus Source Fingerprinting**

| Rainfall Index (mm) | Sediment Yield (t) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Stream Channel sources | | | Unpaved Roads Sources | | | Crop Field Sources | | |
| | Pre- | Post- | Change | Pre- | Post- | Change | Pre- | Post- | Change |
| 15 | 0.018 | 0.043 | +144% | 0.894 | 0.085 | −90% | 1.096 | 0.150 | −86% |
| 30 | 0.045 | 0.197 | +339% | 1.512 | 0.363 | −76% | 2.735 | 0.731 | −73% |
| 60 | 0.152 | 1.641 | +978% | 2.663 | 2.483 | −7% | 7.688 | 5.871 | −24% |

the nutrient content of the sediment, with total P concentrations decreasing from ca. 0.03–0.18 mg kg$^{-1}$ (average of 0.066 mg kg$^{-1}$) during the pre-treatment period to ca. 0.03–0.10 mg kg$^{-1}$ (average of 0.056 mg kg$^{-1}$) in the post-treatment period. Notwithstanding the lack of reduction in sediment concentrations, this reduction in the nutrient content of the sediment is likely to be of ecological benefit. The reduced proportion of sediment derived from the field areas within the catchment is also likely to result in reduced contamination of the sediment by other agrochemicals.

Inspection of the information presented in Fig. 3 indicates that the significant reduction in sediment yield documented for the Arvorezinha catchment and summarised in Table 7, consequent upon improved land management was achieved with a significant proportion of the catchment (20.8%) still under traditional land use. Additional reduction in sediment yield should prove possible if improved management were to be introduced on the remaining areas of the catchment. However, if further reduction in sediment yield is sought, there will be a need to direct attention to reducing sediment mobilisation from stream channels, particularly since this has been shown to have increased in association with the reduction in sediment mobilisation from the field areas.

## Conclusions

The results presented in this contribution have demonstrated the potential for using sediment source tracing techniques to complement more traditional catchment monitoring techniques, when assessing the impact of improved soil management on sediment mobilisation and delivery from agricultural catchments. In the study of the Arvorezinha catchment reported, the use of sediment source tracing technique provided valuable information on the response of the main suspended sediment sources to improved land management and demonstrated that, whilst the introduction of minimum-till practices reduced sediment mobilisation and delivery from the crop field areas and from the unpaved roads within the catchment, this coincided with increased sediment mobilisation from stream channels, thereby reducing the overall reduction in sediment yield. Thus, whilst demonstrating the value of introducing minimum-till practices to reduce sediment mobilisation and delivery, the results of the study also demonstrated the need to take a wider view of catchment management and to also target stream channels if further reductions in sediment yield were required. Table 6 demonstrates that after introduction of improved soil management practices, up to more than 40% of the sediment mobilised from the catchment during individual storm events was derived from stream channels, whereas previously the maximum contribution from stream channels was an order of magnitude less.

The study reported involves a relatively small catchment of only 1.19 km$^2$. The approach is also applicable to larger catchments, although attenuation and storage effects may result in the effects of improved management taking longer to become evident and the relationships between sediment generation and discharge and rainfall parameters, such as those presented in Figs. 5 and 7, may be less well defined. The coupling of sediment source tracing and more traditional monitoring techniques must be seen as providing both an improved understanding of improved management practices on the sediment response of a catchment as well as important information to inform the design and implementation of effective sediment management and control measures.

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