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Investigating sediment sources within a small catchment in southern Italy

PAOLO PORTO[1,2], DES E. WALLING[1] & GIOVANNI CALLEGARI[3]

1 *Department of Geography, University of Exeter, Amory Building, Rennes Drive, Exeter EX4 4RJ, UK*
p.porto@exeter.ac.uk

2 *Dipartimento di Scienze e Tecnologie Agro-Forestali e Ambientali, Università degli Studi "Mediterranea" di Reggio Calabria, Italy*

3 *CNR – Istituto per i Sistemi Agrari e Forestali per il Mediterraneo, Sezione Ecologia e Idrologia Forestale, Rende (Cs), Italy*

Abstract Soil erosion is a serious problem in many areas of Italy, particularly in the south, where rates of soil loss can exceed 100–150 t ha^{-1} $year^{-1}$. Although the impact of these high rates of soil loss has traditionally been assessed in terms of soil degradation, off-site problems related to more general environmental degradation are attracting increasing attention. In order to implement meaningful sediment control strategies, it is necessary to establish both the nature and the location of the main sediment sources within a catchment. Sediment fingerprinting has been increasingly identified as an effective approach for assembling information on suspended sediment sources. The study reported uses source fingerprinting techniques, based primarily on radiometric fingerprints (^{137}Cs and unsupported ^{210}Pb) to establish the primary sediment sources within a small forested catchment (1.38 ha) located in Calabria, southern Italy, where independent information on the spatial pattern of surface erosion rates was available from ^{137}Cs measurements. The source tracing investigation showed that most sediment originates from the south-facing slopes, where the tree cover is discontinuous, emphasizing the importance of vegetation cover in influencing sediment mobilization from the study area. These findings are consistent with the previous work involving ^{137}Cs measurements, which again identified the south-facing slopes with discontinuous tree cover as the areas with the highest rates of soil loss.

Key words caesium-137; erosion rates; lead-210; sediment tracing; soil erosion; source fingerprinting; southern Italy; suspended sediment

INTRODUCTION

Soil erosion is a serious environmental problem in many areas of Italy, particularly in the south where rates of soil loss can exceed 100–150 t ha^{-1} $year^{-1}$. The impact of these high rates of soil loss has traditionally been assessed in terms of soil degradation and loss of productivity, but recent years have also seen an increasing awareness of the off-site problems related to downstream sedimentation and water pollution, which are linked to more general environmental degradation. In order to devise meaningful land-use policies and to design and implement sediment control strategies aimed at reducing off-site problems, it is necessary to establish both the nature and the location of the main sediment sources within a catchment. Sediment source fingerprinting techniques appear to offer considerable scope for providing such information (e.g. Walling & Woodward, 1995; Collins *et al*., 1998; Walling *et al*., 1999), but to date they have not been applied in southern Italy. In order to explore their potential, an investigation was undertaken in a small (1.38 ha) catchment in Calabria, southern Italy, where existing work employing ^{137}Cs had already documented the spatial variability of surface erosion rates within the catchment, particularly in terms of contrasts between the areas with a well developed forest cover and those with only a sparse tree cover. This existing work provided independent information to compare with the results of the fingerprinting exercise.

THE STUDY CATCHMENT

Since the early 1960s, extensive afforestation with *Pinus* and *Eucalyptus* trees has been carried out in Calabria (southern Italy) in an attempt to control soil erosion. The study catchment, located near Crotone (35 m a.s.l., 39°09′02″N, 17°08′10″E), was instrumented in 1978 by the National Research Council of Italy (CNR) in order to monitor the effect of afforestation on hydrological response and sediment yield (Avolio *et al*., 1980; Iovino & Puglisi, 1991). The catchment (W2) has an area of 1.38 ha and forms part of the ephemeral network of the larger Crepacuore basin (Fig. 1), that is incised into Upper Pliocene and Quaternary clays and sandy clays with sandy intercalations (Sorriso-Valvo *et al*., 1995). The catchment has never been cultivated and originally supported a rangeland vegetation cover dominated by *Lygeum spartum* and *Atriplex halimus* (Avolio *et al*., 1980). In 1968 it was planted with *Eucalyptus occidentalis* Engl. and these trees were cut twice (in 1978 and 1990) for timber extraction. After harvesting, the branches and crowns were left *in situ* in order to reduce erosion in the absence of trees. The ephemeral channel network in the study catchment is poorly developed and field observations indicate that such channels are of very limited importance as a sediment source. Equally, such observations emphasize the importance of the catchment slopes as the dominant sediment source.

Prior to afforestation, severe erosion occurred particularly in areas with steep slopes, where any mature soil had been stripped. For this reason, the tree cover is not uniformly distributed throughout the basin and about 20% of the area, located on south-facing slopes, has few trees and retains a sparse grass cover. The dominant soils are classified as regosols and exhibit an Ap-C profile with non-homogenous depth, especially in areas located on the south facing slopes, which show a lower organic matter content and a higher clay percentage, when compared to the rest of the catchment. Representative values for the main soil properties are presented in Table 1.

Table 1 The soil properties of the study catchment.

	Mean	Min.	Max.	SD
Sand (%)	42.1	27.1	60.2	7.5
Silt (%)	29.1	18.6	49.2	4.8
Clay (%)	28.7	7.3	37.8	6.0
P ($\mu g\ g^{-1}$)	984.5	529.5	1423.0	184.2
C (%)	4.2	2.5	13.2	1.9
N (%)	0.2	0.0	0.6	0.1
C/N	34.5	19.1	124.6	17.8

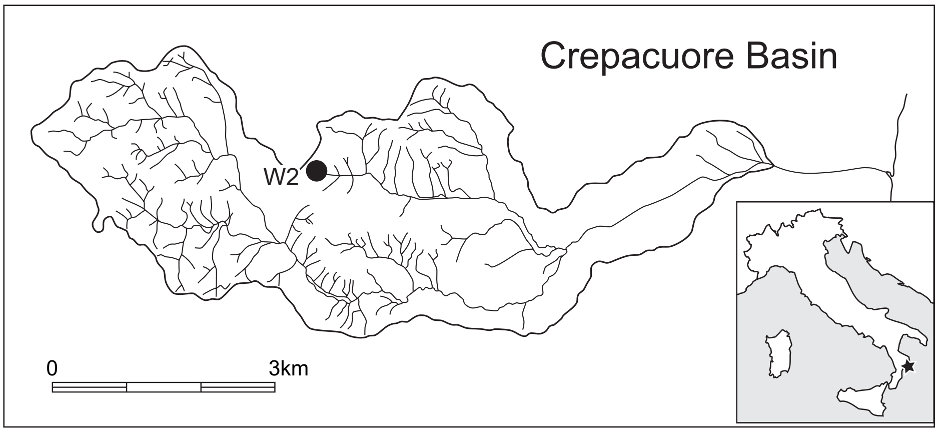

Fig. 1 The study catchment and its location.

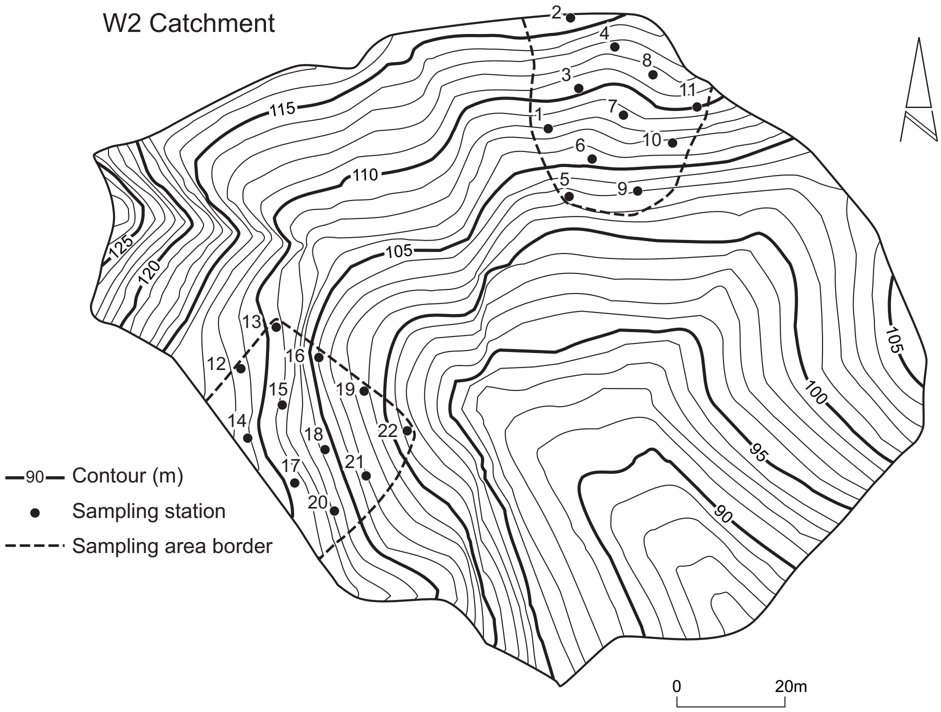

Fig. 2 The location of Plot P1 (top right) and Plot P2 (bottom left) in the study catchment and the sampling points within the two plots.

The climate of the area is typically Mediterranean, with a mean annual precipitation of ~670 mm, most of which falls during the period extending from October to March.

Records of rainfall, runoff and sediment yield are available for the catchment since 1978. Runoff is monitored at the catchment outlet by an H-flume structure equipped with a mechanical stage recorder. The sediment load passing the gauging structure is also measured using a Coshocton wheel sampler installed below the H-flume. In 1991 two large plots (Fig. 2), covering ~1000 m^2, were established within the catchment, in order to measure runoff and sediment yield at the hillslope scale (Callegari *et al*., 1994). These areas have been used in the reported study, because they were considered

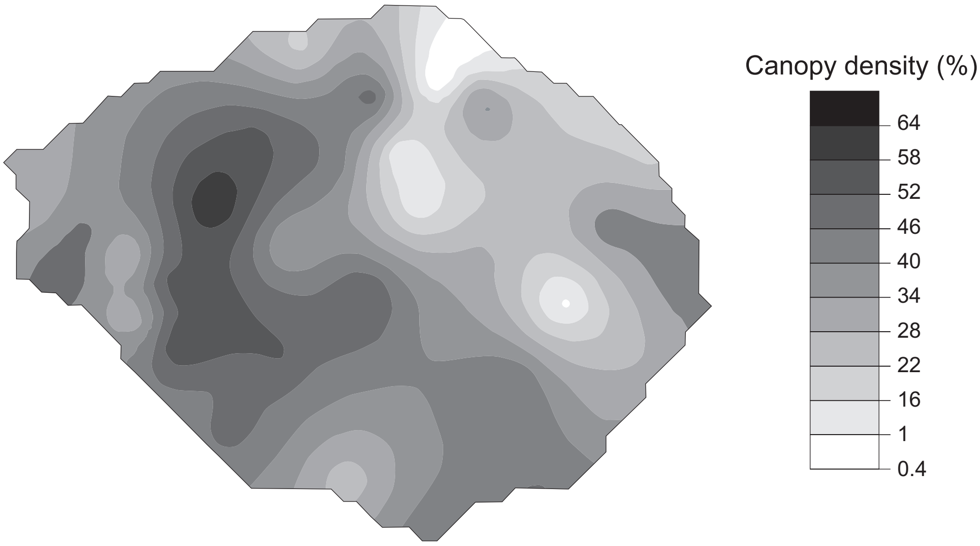

Fig. 3 The variation of canopy cover density within the study catchment.

representative of the two different vegetation covers in the catchment. Plot P1, with a mean slope of 48% and located on a south-facing slope, is characterized by a sparse grass cover which is classified, according to Wischmeier & Smith (1978), as G type, with no appreciable canopy. This plot, with a canopy cover ranging from 0 to 10%, can be considered representative of the south-facing slopes of the catchment. Plot P2, which has a mean slope of 35% and is located on a north-facing slope is covered with *Eucalyptus occidentalis* Engl. This plot, with a canopy cover ranging from ~50 to 60%, can be considered representative of the north-facing slopes of the catchment. A detailed assessment of the canopy cover of the entire catchment is provided in Fig. 3, which was produced in 2002, by taking photographs from 55 points selected for soil sampling in a previous investigation (Porto *et al*., 2001). These two sub-areas were used in this paper, in order to establish the relative contributions to the sediment yield from the catchment of the areas of the catchment characterized by these two contrasting vegetation covers.

FIELD SAMPLING AND LABORATORY PROCEDURES

Several field campaigns were undertaken during the period 2000–2002, in order to collect the source material and bulk suspended sediment samples required for the source fingerprinting exercise. Source material sampling was undertaken in 2001 and involved the collection of representative samples of surface soil from plots P1 and P2. A total of 22 (11 + 11) surface samples were collected from plots P1 and P2, respectively, using the grids shown in Fig. 2. Care was taken only to sample material likely to be eroded (i.e. the top 0–2 cm). Since, as indicated above, the ephemeral channel network could be discounted as representing a significant sediment source, the samples from the two plots were judged to represent the two main potential sources. Time-integrated samples of suspended sediment were collected from the catchment outlet for seven events that occurred during the period September 2000–April 2001. These samples were collected from the storage tanks associated with the Coshocton Wheel sampler and consisted almost exclusively of <63 μm particles.

Laboratory analysis of both source material and suspended sediment samples encompassed a range of potential fingerprint properties including organic and inorganic constituents (total C and N, and organic and inorganic P), as well as radiometric (^{137}Cs, ^{210}Pb) measurements. In order to permit direct comparison between the properties of source materials and suspended sediment, the <63 μm fractions of both sets of samples were separated by sieving, dried and disaggregated prior to gamma spectrometry and analysis for P, C and N content.

The P content (total (TP), inorganic (IP) and organic (OP)) of source materials and suspended sediment samples, was determined using a Pye Unicam SP6 UV/visible spectrophotometer after chemical extraction (Mehta *et al*., 1954). Total carbon (C) and nitrogen (N) concentrations were measured using a Carlo Erba ANA 1400 automatic nitrogen analyser. The ^{137}Cs and unsupported ^{210}Pb activities in the soil and sediment samples were measured simultaneously by gamma-ray spectrometry, using a high-resolution coaxial HPGe n-type coaxial detector. Count times were typically ~30000 s, providing results with an analytical precision of ~10% at the 95% level of confidence. The total ^{210}Pb concentrations of the samples were obtained using the 46.5 keV gamma-ray for ^{210}Pb, and the ^{226}Ra concentrations required to calculate the supported component were obtained using the 351.9 keV gamma-ray for ^{214}Pb, a short-lived daughter of ^{226}Ra. The ^{137}Cs activities in the samples were obtained from the counts at the 662 keV peak in the measured γ-ray spectrum.

FINGERPRINTING SOURCE MATERIALS

The concentrations of ^{137}Cs and unsupported ^{210}Pb associated with surface material collected from the two plots are summarized in Table 2. The mean values for Plot 1 (4.3 and 18.1 Bq kg^{-1} for ^{137}Cs and unsupported ^{210}Pb, respectively) are substantially lower than those associated with plot P2 (22.6 and 50.6 Bq kg^{-1}, respectively). This reflects the higher erosion rates in the areas with south-facing slopes, since both radionuclides are characterized by an exponential depth distribution in undisturbed soils and erosion will remove the surface horizons containing higher radionuclide activities. In order to confirm the statistical significance of this contrast, the Mann-Whitney test was used to test the significance of the difference between the means for plots P1 and P2 for both ^{137}Cs and unsupported ^{210}Pb concentrations. The resulting values ($p < 0.05$) indicated that there is a significant difference between the two plots in terms of the radionuclide concentrations.

Table 2 Mean values for selected fingerprint properties of source materials and suspended sediment samples collected from the catchment outlet.

Material	Unsupported ^{210}Pb (Bq kg^{-1})	^{137}Cs (Bq kg^{-1})	TP (μg g^{-1})	IP (μg g^{-1})	OP (μg g^{-1})	N (%)	C (%)	C/N
Plot P1	18.1	4.3	1075	560	516	0.08	3.1	39.8
Plot P2	50.6	22.6	932	464	467	0.19	4.6	24.5
Sediment	19.8	1.6	1034	553	481	0.06	2.8	45.2

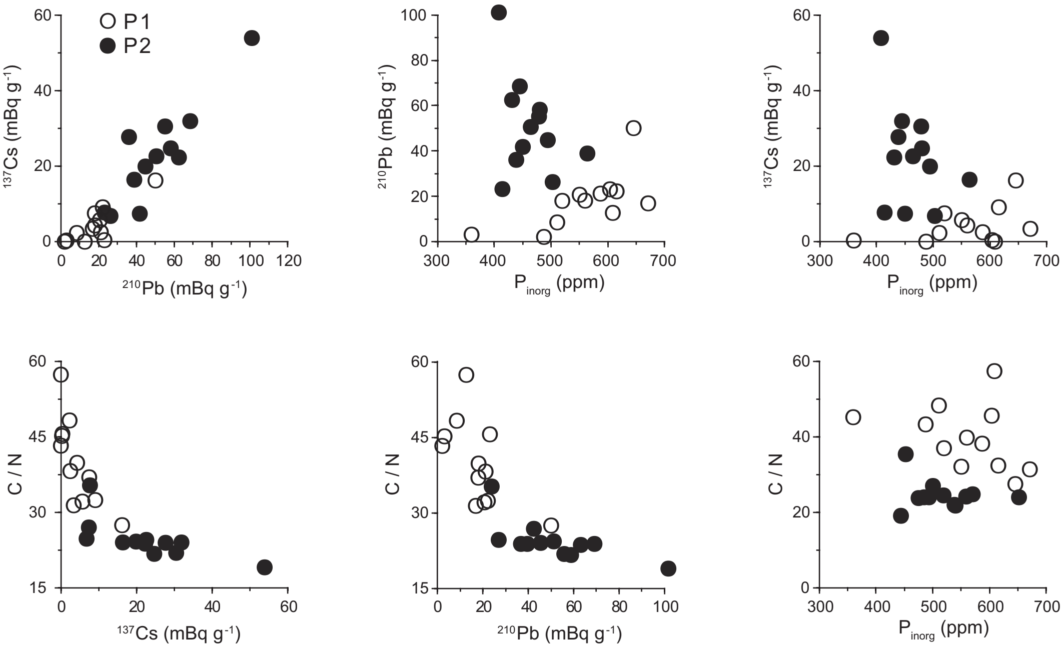

Fig. 4 The relationship between selected fingerprint properties for the <63-µm fractions of the source material samples collected from plots P1 and P2.

Table 2 also provides information on the P and total C and N contents of the same samples. The high C/N ratios reflect the low fertility of soil under the eucalyptus forest due to the slow litter decomposition. The same statistical analysis (Mann-Whitney test) has been employed to test for a significant difference between the mean values of the P, C and N contents for the two plots. The resulting *p* values were again significant at the 0.05% level for all the fingerprint properties, confirming the difference in surface material properties between the two plots.

The potential for using these measurements to fingerprint the two main sediment sources in the study catchment is demonstrated in Fig. 4, which indicates that the two sets of source materials (from plots P1 and P2) can be clearly distinguished in terms of their ^{137}Cs and unsupported ^{210}Pb concentrations as well as their IP concentrations and C/N ratios.

COMPARING THE FINGERPRINTS OF THE POTENTIAL SOURCE MATERIALS WITH THOSE OF SUSPENDED SEDIMENT

Table 2 also presents information on the fingerprint properties (^{137}Cs and unsupported ^{210}Pb activities, IP contents and C/N ratios) of suspended sediment collected at the catchment outlet for the seven events. These values are then compared with those associated with potential source materials (P1 and P2) in Fig. 5. The evidence provided in Fig. 5 and Table 2 indicates that the suspended sediment exhibits ^{137}Cs and unsupported ^{210}Pb activities, IP concentrations and C/N ratios which are directly comparable with those from Plot P1. In order to confirm this conclusion, a Mann-Whitney test was again used to test the significance of the difference between the means for Plot P1 and for the sediment collected at the catchment outlet for all the

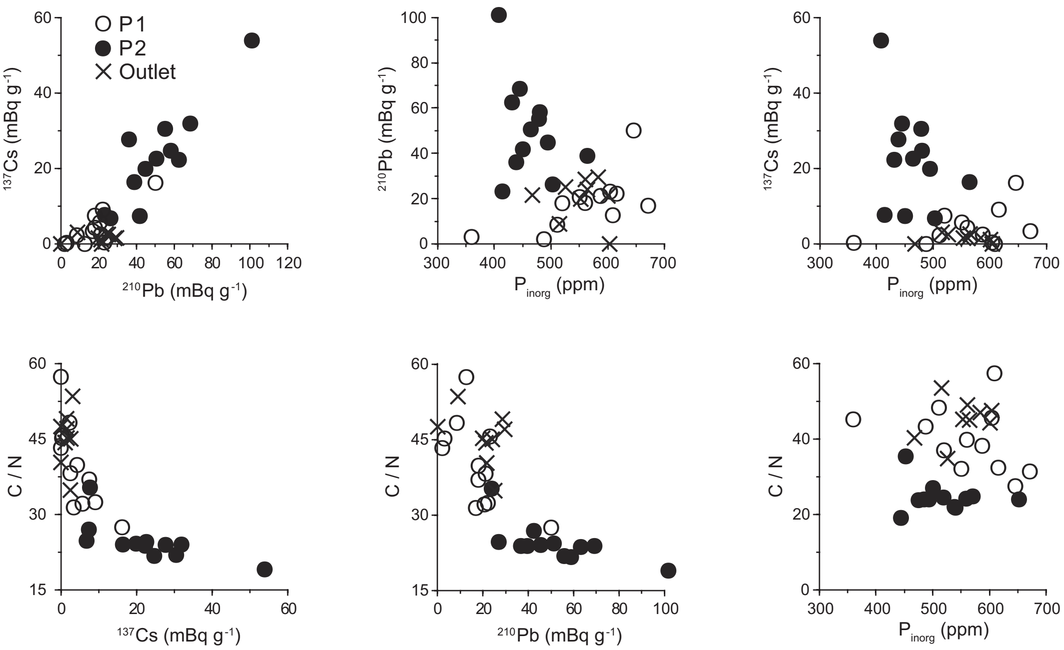

Fig. 5 The relationship between selected fingerprint properties for the <63-µm fractions of the source material samples collected from plots P1 and P2 and the sediment samples collected from the catchment outlet.

fingerprint properties. The resulting *p* values were not significant at the 0.05% level, indicating that there is no significant difference between the two data sets in terms of radionuclide concentrations, IP contents and C/N ratios. Use of the same test to compare the means from Plot P2 with those for suspended sediment gave significant *p* values at the 0.05% level, confirming that a significant difference existed between the properties of surface materials from Plot P2 and suspended sediment collected from the catchment outlet and thus that surface material from the areas with north-facing slopes provides only a minor contribution to the sediment sampled at the catchment outlet, compared to that from the south facing slopes.

Although the fingerprint evidence provided in Fig. 5 and Table 2 confirms that the dominant sediment sources in this catchment are the areas with south-facing slope, it cannot quantify the relative contributions from the two potential sources. Furthermore, it does not directly integrate the evidence provided by the different fingerprint properties. A multivariate mixing model was therefore applied to a composite fingerprint comprising several fingerprint properties, to provide quantitative estimates of the relative contributions of the two potential sources to the sampled sediment load.

Following Walling *et al.* (1993) and assuming that the fingerprint property concentrations in any given suspended sediment sample are dependent upon the corresponding concentrations in the original source materials and the relative contributions of the various potential sources to the sediment sample, a mixing model can be used to establish the relative contribution of the two potential source areas identified in this study. The mixing model must satisfy the following constraints:

– the contribution of each source must be non-negative, i.e.:

$$0 \le P_S \le 1 \tag{1}$$

– the contributions of the different sources to the suspended sediment load sampled at the corresponding basin outlet must sum to unity, i.e.:

$$\sum_{S=1}^{n} P_S = 1 \tag{2}$$

A linear equation can then be established for each property contained within the composite fingerprint. The resultant set of linear equations is generally over-determined, and the estimates for the relative contributions from the potential sources can be optimized by minimizing the following objective function (Walling *et al.*, 1993):

$$\sum_{i=1}^{n} \left\{ \left[C_i - \left(\sum_{S=1}^{m} P_S \, S_{S,i} \right) \right] / C_i \right\} \tag{3}$$

where C_i is the concentration of fingerprint property i in the suspended sediment sample, P_s is the optimized percentage contribution from source area s, S_{si} is the mean concentration of fingerprint property i in source area s, m is the number of source areas, and n is the number of tracer properties.

Table 3 lists the estimates of the relative contributions of the two potential sources obtained using the above mixing model for each event. In all cases the contribution from the south-facing slopes is seen to be dominant, with the mixing model indicating that this source accounted for 100% of the sediment sampled at the catchment outlet. These results confirm those provided by Fig. 5, which emphasized the importance of the south facing slopes as the main sediment source.

Table 3 The relative contributions of source materials represented by plots P1 and P2 to the sediment output from the study catchment for seven sampled events.

Date of sampled event	11 Sep. 2000	6 Oct. 2000	7 Nov. 2000	6 Dec. 2000	2 Jan. 2001	25 Jan. 2001	3 Apr. 2001
Rainfall (mm)	177	149	25	42	34	177	93
Runoff (m^3)	78	370	nd	nd	238	368	78
Sediment yield (t ha^{-1})	4.6	1.7	nd	nd	31.6	3.5	0.8
% Plot 1	100	100*100*	100	100	100	100	100
% Plot 2	0	0* 0*	0	0	0	0	0

* Sediment samples were collected from both storage tanks during this event.

DISCUSSION AND CONCLUSIONS

Although the results produced by the mixing model and presented in Table 3 are listed as single values for the percentage contribution (i.e. 100%), it should be recognized that the procedures used to derive these values involve many uncertainties, for example in using a single mean value to characterize a fingerprint property for a particular source. Furthermore, a number of simplifying assumptions have been made. These, for example, include assumptions that channel erosion does not contribute to the sediment flux at the catchment outlet and that complications introduced by size-selective erosion and deposition, and thus contrasts in the particle size composition between the source material samples and the samples of suspended sediment collected at the basin outlet, can be accounted for by restricting attention to the <63 μm fractions of both sample sets. As a result, the values of 100% contribution from the south-facing slopes of the study catchment should be seen as indicating that this source area is by far the most dominant of the two sources, rather than the exclusive source of the sediment flux at the catchment outlet.

Against this background, the results from the fingerprinting investigation can be seen as being highly consistent with the evidence provided by previous work in the catchment aimed at using ^{137}Cs measurements to documents the magnitude and spatial variability of surface erosion rates within the study catchment (see Porto *et al*., 2001, 2003, 2004). This previous work showed that rates of soil loss were substantially greater from the areas of the study catchment with a discontinuous tree cover, than from the areas with a good tree cover. Based on ^{137}Cs measurements undertaken on soil cores collected at points adjacent to those from which the source material samples were collected within plots P1 and P2, the mean annual erosion rate over the past *c.* 45 years from Plot P1, which is representative of the more rapidly eroding south-facing slopes with a discontinuous tree cover, was 18.9 t ha^{-1} $year^{-1}$. In contrast, the equivalent erosion rate for Plot P2, with a good forest cover, was very significantly lower at 7.6 t ha^{-1} $year^{-1}$. It should be recognized that these estimates of erosion rates for the two potential source areas within the study catchment represent average values for the past *c.* 45 years. As such, they could be expected to provide a meaningful estimate of contemporary erosion rates from Plot P1 and the south-facing areas of the catchment with sparse tree cover. However, the erosion rates estimated for Plot P2 and the north-facing areas of the catchment are likely to *overestimate* contemporary erosion rates from those areas, since the longer-term estimates provided by the ^{137}Cs measurements will include both a period prior to forest planting in 1968 and periods when the trees were cut and the tree cover was therefore sparse in the late 1970s and early 1990s. During these times, erosion rates from the north-facing slopes of the catchment could be expected to be substantially higher than at present, when a good tree cover exists. It is therefore not unreasonable to assume that contemporary erosion rates on the south facing slopes are about 5–10 times greater than on the north-facing slopes with a good tree cover. This situation would be consistent with the results provided by the mixing model, which indicate that the majority of the sediment currently discharged from the study catchment has been mobilized from the south facing slopes.

The results presented above confirm the potential for using source fingerprinting techniques to establish the main sediment sources in this environment. For other catchments, it may be necessary to include cultivated areas as another potential source area, and, where larger catchments are involved, channels and gullies will also need to be included as potential sources. In addition, the results from the source fingerprinting investigation provide clear evidence of the effectiveness of planting eucalyptus trees in degraded areas, in reducing soil erosion and sediment generation as previously argued by Iovino & Puglisi (1991), Cinnirella *et al*. (1998) and Sorriso-Valvo *et al*. (1995). The estimates of erosion rates in the study catchment provided by ^{137}Cs measurements indicate that prior to the planting of eucalyptus trees, the total sediment contribution from the 80% of the catchment that now supports a good forest cover was probably about double that from the remaining 20% of the catchment, characterized by south-facing slopes, which currently support only a sparse tree cover. At present, the sediment contribution from the 80% of the catchment with a good tree cover accounts for only a minimal proportion of the sediment load at the catchment outlet.

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