Validating the use of caesium-137 measurements to estimate erosion rates in three small catchments in Southern Italy

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Abstract The fallout radionuclide caesium-137 (^{137}Cs) has been increasingly used in recent years to assess soil erosion and deposition at the catchment scale. However, the successful application of the ^{137}Cs approach depends heavily on the availability of reliable conversion models for converting measurements of ^{137}Cs redistribution to estimates of soil redistribution rates. This paper reports the results of a study aimed at validating the use of a theoretical conversion model to convert measurements of ^{137}Cs inventories on uncultivated soils to estimates of soil erosion rates. It is based on three small catchments located in Calabria, Southern Italy, for which measurements of sediment output are available. By comparing the estimates of net soil loss from the catchments derived from ^{137}Cs measurements with the measured sediment output, it is possible to assess the accuracy of the former estimates. The general correspondence between the measured sediment yields and the estimates of net soil loss based on ^{137}Cs measurements, confirms the validity of the theoretical model used for converting ^{137}Cs measurements into estimates of soil redistribution rates.

Key words caesium-137; conversion models; erosion rates; Italy; sediment yield; soil erosion

INTRODUCTION

Increasing concern for both the on-site and off-site impacts of soil erosion in many areas of the world has focused attention on the need to assemble reliable information on rates of erosion and soil redistribution under different environmental conditions. Traditional measurement techniques possess many limitations (Loughran, 1989) and in recent years the potential for using environmental radionuclides, and more particularly caesium-137 (^{137}Cs), has attracted increasing attention (Walling, 1998). However, the successful application of the ^{137}Cs technique depends on the reliability of the conversion model used to convert radiocaesium measurements to estimates of soil redistribution rates. In the absence of empirical conversion models, most conversion models have a theoretical basis and make use of existing understanding of the fate and behaviour of ^{137}Cs in eroding soils to derive a relationship between the erosion or deposition rate and the reduction of the ^{137}Cs inventory relative to the local reference inventory. Several of the assumptions associated with these theoretical conversion models are essentially untested and the models remain largely unvalidated. This paper reports the results of an ongoing study aimed at validating the use of ^{137}Cs measurements to estimate soil redistribution rates on three small catchments with forest and rangeland land use located in Calabria, Southern Italy. Long-term measurements of sediment output are available for the catchments, and by comparing these measurements with estimates of net soil loss from the catchments derived from ^{137}Cs measurements, the accuracy of the latter estimates can be assessed. Some results for two of these catchments have been published previously (Porto *et al.*, 2001, 2003), but this paper introduces data from a third contrasting catchment and provides an overall assessment of the validity of the estimates of erosion rates derived for the catchments using ^{137}Cs measurements coupled with a theoretical conversion model, based on the results from all three catchments.

THE STUDY CATCHMENTS

The three small catchments investigated in this study are located near Crotone in Calabria, Southern Italy (35 m a.s.l., 39°09′02″N, 17°08′10″E). The three catchments, W1, W2, and W3, have drainage areas of 1.47, 1.38 and 1.65 ha respectively and are located in the ephemeral headwaters of the larger Crepacuore basin (Fig. 1), which is incised into the local Upper Pliocene and Quaternary clays, sandy clays and sands. The catchments have never been cultivated. Catchment W1 supports a rangeland vegetation cover, and catchments W2 and W3 were planted with *Eucalyptus occidentalis Engl.* in 1968. These trees have been cut twice (in 1978 and 1990) in catchment W2, and once (in 1986) in catchment W3. The tree cover within catchment W2 is not uniform, and about 20% of the area, located on south facing slopes, is characterized by discontinuous tree and grass cover. In catchment W3, the tree cover is almost continuous and only about 2–3% of the area supports grass. Further details of the topography of the study catchments and the texture of their soils are provided in Table 1. 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.

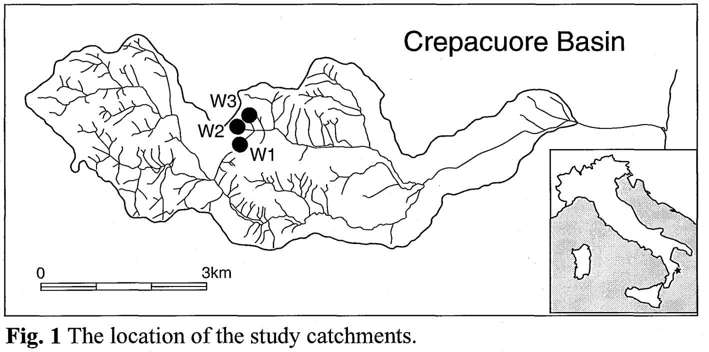

Fig. 1 The location of the study catchments.

Table 1 The characteristics of the study catchments.

Catchment	Drainage area (ha)	Mean altitude (m a.s.l.)	Mean slope (%)	Soil texture Sand (%)	Silt (%)	Clay (%)	Sediment yield (t ha^{-1} year^{-1}): Min	Max	Mean
W1	1.473	122	53	14	44.5	41.5	5.1	38.4	11.6
W2	1.375	103	35	14.6	49.2	36.2	1.7	98.5	20.8
W3	1.654	98	24	20.7	45.5	33.8	2.9	25.7	7.6

In 1978, these catchments were instrumented for measuring rainfall, runoff and sediment yield (Cantore *et al.*, 1980). Precipitation has been recorded using a tipping bucket raingauge and runoff is measured at the outlet of each catchment using an H-flume structure equipped with a mechanical stage recorder. The sediment load passing the gauging structure is measured using a Coshocton wheel sampler installed below the H-flume (Porto *et al.*, 2003).

SEDIMENT YIELDS AT THE CATCHMENT OUTLETS

Sediment yield data available for the catchments for the period 1978 to 1994 (Cantore *et al.*, 1994) have been used in this study. Due to malfunctioning of the sediment sampling equipment in the catchments during some events, values of annual sediment yield are not available for all years. Where the number of unmonitored events was limited, the sediment loads associated with these events have been estimated using the Sediment Delivery Distributed (SEDD) model (Ferro & Porto, 2000) and incorporated into the record. The annual sediment yields for the catchments are shown in Fig. 2 and the range of annual sediment yields documented for each catchment is listed in Table 1.

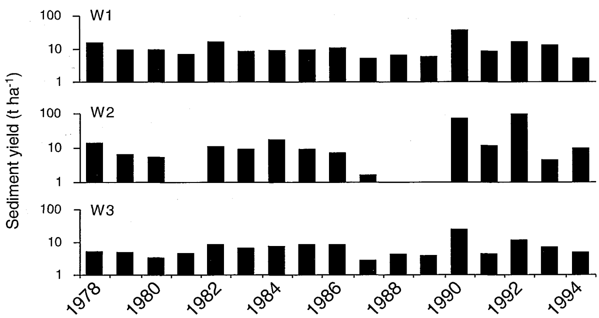

Fig. 2 Measured annual suspended sediment yields from the study catchments during the period 1978–1994.

In order to provide values of sediment yield for the individual catchments relating to the period represented by the ^{137}Cs measurements, the measured data have been extrapolated to cover the period 1956–1998. For catchment W1, the grass cover was assumed to have remained essentially constant over the period 1956–1998 and a simple logarithmic regression between event sediment yield and event rainfall, based on 46 discrete events, was used. Since trees were absent from catchments W2 and W3 during the first 12 years of the period in question and the cover density varied during the remainder of the period under consideration, in response to tree growth and forest harvesting, a multiple regression analysis, involving both event rainfall and an estimate of the time variant cover density based on the age of the trees, was used to develop the equations for predicting event sediment yields from these two catchments (Porto *et al.*, 2003). In the case of catchment W3, both variables were included in the final prediction equation as significant ($p > 0.01$), but for catchment W2 event sediment yield was only significantly related ($p > 0.01$) to event rainfall. The estimates of mean annual sediment yield for the period 1956–1998 for the three study catchments are presented in Table 2, along with the prediction equations used.

Table 2 Relationships for sediment yield calculation.

Catchment	Equation type	Parameters: a	b	c	r	Y (t ha^{-1})
W1	$Y = aX_1^b$	0.0011	1.72	–	0.64	12.4
W2	$Y = aX_1^b$	0.0027	1.69	–	0.86	19.2
W3	$Y = aX_1^b X_2^c$	0.0033	1.49	–0.17	0.84	7.8

X_1 = rainfall amount (mm); X_2 = canopy cover (%); r = correlation coefficient; Y = mean annual sediment yield 1956–1998.

SOIL SAMPLING AND ^{137}Cs ANALYSIS

Soil sampling within the study catchments involved several campaigns. The first campaigns, which focused on catchments W2 and W3 and the reference sites, were undertaken in 1998, 1999 and 2001 and are described in a previous paper (Porto *et al.*, 2003). The final campaign, undertaken within catchment W1, involved the collection of 68 bulk cores. The cores were collected at the intersections of an approximate 20 m × 10 m grid, with additional cores to take account of topographic variability. The samples were collected using a steel core tube (6.9 cm diameter) driven into the ground by a motorized percussion corer and subsequently extracted using a hand-operated winch.

The samples used to establish the reference inventory were collected from three different areas and following Porto *et al.* (2003) they are referred to as:

- Reference site 1: located in catchment W1 within an area characterized by permanent grassland with minimal slope;
- Reference site 2: located in catchment W3 within a small clearing between the trees;
- Reference site 3: located within adjacent undisturbed rangeland with some scattered oaks (*Quercus pubescens*) at a similar altitude to the study catchments. This third site was selected because of the difficulties in finding an undisturbed area within catchment W2.

At the reference sites, a scraper plate (Campbell *et al.*, 1988) was used to collect samples at depth increments ranging from 1 to 4 cm, to a depth of 50 cm. Six additional 8.6-cm diameter bulk soil cores were collected from each reference site, in order to take account of the local variability of ^{137}Cs inventories. Additional scraper plate samples were obtained from several representative eroding and depositional locations within the study catchments, in order to document the ^{137}Cs depth distribution.

All bulk core and depth incremental scraper plate samples were oven dried at 105°C for 48 h, mechanically disaggregated and dry sieved to recover the <2 mm fraction. A representative sub-sample of this fraction was packed into a plastic Marinelli beaker for determination of ^{137}Cs activity by gamma spectrometry. The measurements were made using high resolution HPGe detectors in the laboratories of the Department of Nuclear Engineering at the University of Palermo, Italy and the Department of Geography at the University of Exeter, UK. Count times were typically approx. 30000s, providing a precision of about ±10% at the 95% level of confidence. All ^{137}Cs measurements were standardized to a fixed date at the end of 2001.

^{137}Cs inventories and depth distributions at the reference sites

The ^{137}Cs inventories obtained for the three reference sites ranged from 2430 to 2492 Bq m^{-2} with a mean value of 2456 Bq m^{-2} (Porto *et al.*, 2003). The ^{137}Cs depth distributions

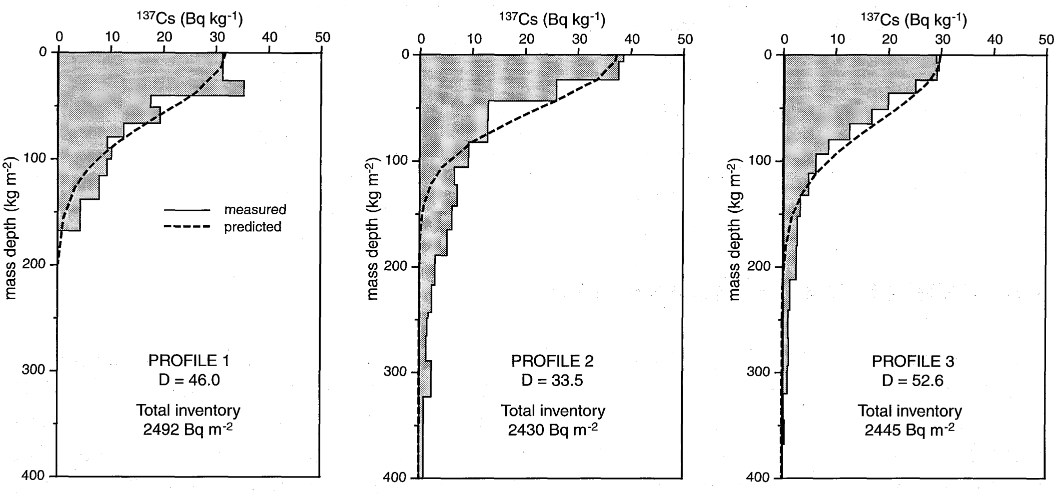

Fig. 3 The ^{137}Cs depth distributions documented for reference sites 1, 2 and 3 and the results of fitting the diffusion and migration model (equation 1) to these profiles.

associated with these profiles are depicted in Fig. 3. The shape of these profiles, showing a steady (exponential) decline with depth from a maximum at, or immediately below, the soil surface, conforms to that expected from undisturbed locations (see Walling & Quine, 1992).

^{137}Cs inventories within the study catchments

The range of the values of ^{137}Cs inventory obtained for the 68 bulk cores collected from catchment W1, and standardized to the year 2001, are listed in Table 3 together with the equivalent values for the samples collected previously from catchments W2 and W3. All values of ^{137}Cs inventory for the cores collected from catchment W2 and W3 are less than the local reference inventory (2456 Bq m^{-2}), suggesting that the surfaces of both catchments have been dominated by net soil loss over the period covered by the ^{137}Cs measurements. In the case of catchment W1, however, the inventories for some cores exceeded the reference inventory, pointing to the existence of depositional areas. Figures 4(a) and 4(b) provide two typical examples of the depth distribution of ^{137}Cs for sampling points within the study catchments. That shown in Fig. 4(a) is representative of an eroding site in catchment W2, whereas that shown in Fig. 4(b), which was collected from catchment W1, is characterized by an inventory greater than the local reference value and is therefore indicative of a depositional site.

Table 3 ^{137}Cs inventories within the study catchments.

Catchment	Min (Bq m^{-2})	Max (Bq m^{-2})	Mean (Bq m^{-2})
W1	4.1	4053	1395
W2	18	2429	867
W3	81	2430	1070

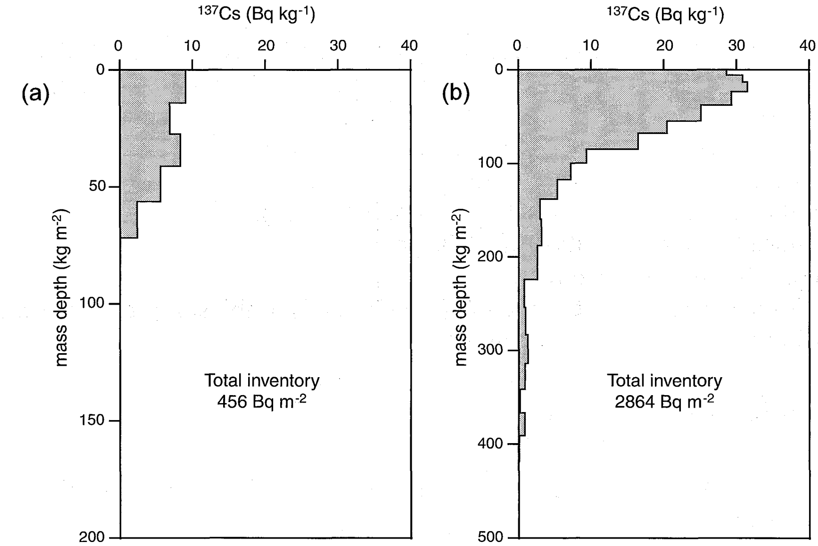

Fig. 4 Representative ^{137}Cs depth distributions for an eroding site in catchment W2 (a) and a depositional site in catchment W1 (b).

USING ^{137}Cs MEASUREMENTS TO ESTIMATE EROSION RATES

Estimation of erosion and deposition rates from ^{137}Cs measurements is commonly based on a comparison of the inventory measured at a specific point with the reference inventory and on the degree of reduction or increase of that inventory. The conversion models, used for uncultivated land to convert the magnitude of the reduction or increase in the ^{137}Cs inventory to an estimate of the rate of soil loss or deposition, employ different theoretical representations of the vertical distribution of ^{137}Cs within the soil and its evolution through time (see Walling & He, 1999). The simple profile distribution model assumes a standard time-invariant exponential depth distribution, which is truncated by erosion, whereas the diffusion and migration model proposed by Walling & He (1999) attempts to model the interaction of surface lowering by erosion with the progressive development of the depth distribution, in response to continuing fallout inputs to the surface and downward diffusion and migration of the radiocaesium.

In this study attention has focused on the diffusion and migration model, which has been shown by Porto *et al.* (2003) to produce more consistent and reliable results than the profile distribution model. Further details of this model can be found in Porto *et al.* (2003), but its main features are briefly summarized below.

The vertical distribution of ^{137}Cs within a soil will vary through time in response to the time-dependent fallout input and the post-depositional redistribution of ^{137}Cs within the profile. For soils with high erosion rates, assuming a constant soil lowering E (kg m^{-2}) and diffusional transport, the vertical distribution of ^{137}Cs within a soil, for any cumulative mass depth and time t', can be expressed (Porto *et al.*, 2003) as:

$$C_e(x,t,t') = \mathrm{e}^{-\lambda(t-t')} \int_0^{\infty} \frac{I(t')}{H} e^{-\frac{y}{H}} \left\{ \left[e^{-\frac{[(x+E)+y]^2}{4D(t-t')}} + e^{-\frac{[(x+E)-y]^2}{4D(t-t')}} \right] \frac{1}{\sqrt{4\pi D(t-t')}} \right\} \mathrm{d}y \qquad (1)$$

where:
y = integration variable which indicates the depth of soil involved in ^{137}Cs diffusion;
$C_e(x,t,t')$ = the concentration of ^{137}Cs for any cumulative mass depth x and time t' (Bq kg^{-1});
D = the effective diffusion coefficient (kg^2 m^{-4} year^{-1});
H = the relaxation depth expressed as a mass depth (kg m^{-2});
λ = the decay constant for ^{137}Cs (0.023 year^{-1});
x = the mass depth from the soil surface downwards (kg m^{-2});
t = the time since the first deposition of ^{137}Cs (year);
$I(t')$ = the input (Bq m^{-2} year^{-1}) at time t'.

The ^{137}Cs concentration distribution $C_e(x,t)$ (Bq kg^{-1}) in the soil profile at time t can be obtained by integrating $C_e(x,t,t')$ over time t':

$$C_e(x,t) = \int_0^t C_e(x,t,t')\mathrm{d}t \qquad (2)$$

Integration of $C_e(x,t)$ over mass depth x gives the total ^{137}Cs inventory A_u (Bq m^{-2}) for an erosion site at time t:

$$A_u(t) = \int_0^\infty C_e(x,t)\ \mathrm{d}x \qquad (3)$$

Assuming a constant value of H (5 kg m^{-2}), as suggested by Walling & He (1999), equations (1) and (3) can be solved simultaneously for E (kg m^{-2}), with A_u (Bq m^{-2}) representing the measured inventory at an eroding point. The erosion rate R (kg m^{-2} year^{-1}) may then be estimated by dividing the quantity E by the time $t - t_0$ (year) since the commencement of ^{137}Cs fallout. Equation 1 can be fitted to the ^{137}Cs depth distribution at reference locations where E = 0. This was achieved by calculating the parameter D for each profile using least squares. The results of this fitting are depicted in Fig. 3.

For a depositional site, the deposition rate D_R can be estimated from the ^{137}Cs concentration in deposited sediment $C_d(t')$ and the excess ^{137}Cs inventory (defined as the total measured ^{137}Cs inventory A_u less the local reference inventory A_{ref}) using the following relationship (Walling & He, 1999):

$$D_R = \frac{A_u - A_{ref}}{\int_{t_0}^{t} C_d(t')\, e^{-\lambda(t-t')}\mathrm{d}t'} \qquad (4)$$

Assuming that the ^{137}Cs concentration $C_d(t')$ of deposited sediment can be represented by the weighted mean of the ^{137}Cs concentration of the sediment mobilized from the upslope contributing area, $C_d(t')$ can be calculated as:

$$C_d(t') = \frac{1}{\int_S R\, dS} \int_S C_e(t')\, R\, \mathrm{d}S \qquad (5)$$

where S (m^2) is the upslope contributing area and $C_e(t')$ (Bq kg^{-1}) is the ^{137}Cs concentration of sediment mobilized from an eroding point, which can be calculated from equation (1), for $x = 0$.

COMPARISON OF THE ESTIMATES OF SOIL LOSS DERIVED FROM THE ^{137}Cs MEASUREMENTS WITH THE SEDIMENT OUTPUT

The diffusion and migration model provided point estimates of soil redistribution rates (t ha^{-1} year^{-1}), based upon the ^{137}Cs inventories measured for individual soil cores. These point values were interpolated using a kriging procedure to derive a spatially representative estimate of net soil loss for each catchment.

Table 4 provides a comparison between the measured sediment output from the three study catchments and the equivalent estimates of total or net soil loss obtained from the ^{137}Cs measurements. The conversion models were parameterized using the three reference profiles depicted in Fig. 4 and three estimates of soil loss are therefore provided. As reported in previous papers (Porto *et al.*, 2001, 2003), there was no evidence of significant deposition within catchments W2 and W3. In this case, a direct comparison between the estimates of total soil loss derived from the ^{137}Cs measurements and the measured sediment output from the catchments is possible. In contrast, for catchment W1, where evidence of deposition was found, Table 4 lists the estimates of gross soil loss, total deposition, and net soil loss.

Table 4 Comparison between measured and calculated erosion rates using the proposed model (t ha^{-1} year^{-1}).

Profile	Total soil erosion W1	Total deposition W1	Net soil erosion: W1	W2	W3
	Equation (1) and (3)	Equation (4)	Equation (1) and (3)		
1	8.84	0.19	8.6	14.0	11.3
2	7.34	0.18	7.2	11.8	9.4
3	9.16	0.23	8.9	14.7	11.7
Mean annual sediment yield			12.4	19.2	7.8

Table 4 indicates that the estimates of soil loss from the three study catchments derived from the ^{137}Cs measurements using the diffusion and migration conversion model are reasonably consistent with the measured sediment outputs from the catchments. Very close agreement would not necessarily be expected, since both the measured sediment yields and the estimates of net soil loss derived from the ^{137}Cs measurements involve a number of potential errors and uncertainties. For example, the estimates of net soil loss for the individual catchments derived from the ^{137}Cs measurements are clearly sensitive to the number and precise location of the sampling points and uncertainties due to sampling and analytical precision and the spatial interpolation procedure employed. Similarly, the estimates of sediment output from the catchments, based on the measured sediment fluxes, are subject to various uncertainties relating to the measurement procedures, as well as the procedure used to extrapolate the measurements to the longer period covered by the ^{137}Cs measurements. In this context, it can be seen that the relative magnitudes of the estimates of soil loss derived from the ^{137}Cs measurements are not entirely consistent with those of the measured sediment yields. Although both values are highest for catchment W2, the lowest values of sediment yield are associated with catchment W3, whereas the lowest values of estimated soil loss are associated with catchment W1. Furthermore, whereas the measured sediment yields exceed the estimates of soil loss for catchments W2 and W1, the reverse situation exists for catchment W3.

CONCLUSIONS

The broad agreement between the magnitude of the estimates of sediment output from the three study catchments and the estimates of soil loss from the catchments derived from ^{137}Cs measurements, provides a clear confirmation of the validity of the ^{137}Cs technique for estimating erosion and deposition rates from uncultivated areas in general, and of the diffusion and migration conversion model in particular. The differences between the measured sediment yields and the estimates of soil loss derived from the ^{137}Cs measurements may reflect the uncertainties associated with the two approaches. Equally, they could reflect minor limitations in the results provided by the ^{137}Cs measurements. In this context, it is possible that the contrast between the forested (W2 and W3) and grassland (W1) catchments is not adequately represented by the conversion model or the ^{137}Cs depth profiles documented for the reference sites. Further work is clearly required to investigate these minor inconsistencies.

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