Relating caesium-137 and soil loss from cultivated land

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Abstract

Because of the limitations associated with traditional methods of measuring rates of soil erosion, such as erosion plots, the fallout radionuclide caesium-137 ($^{137}$Cs) has been increasingly used in recent years as an alternative approach to estimating rates of soil redistribution on both cultivated and noncultivated areas. The successful application of the $^{137}$Cs approach depends heavily on the availability of reliable conversion models for converting measurements of $^{137}$Cs redistribution, relative to the local reference inventory, to estimates of soil redistribution rates. In the absence of empirical conversion models, most studies have made use of theoretical conversion models. The assumptions made by such theoretical models are frequently untested and they thus remain largely unvalidated. This contribution describes the results of a measurement programme involving nine experimental plots located in southern Italy, aimed at validating several of the basic assumptions commonly associated with the use of mass balance models for estimating rates of soil redistribution on cultivated land from $^{137}$Cs measurements. Overall, the results confirm the general validity of these assumptions. However, several other assumptions and process representations incorporated into such models still require testing and elucidation.

Keywords: Erosion plots; Soil erosion; Caesium-137; Conversion models; Particle size

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1. Introduction

In view of the many limitations associated with traditional approaches to documenting soil erosion rates (cf. Loughran, 1989), the potential for using fallout radionuclides as tracers in soil erosion investigations has been increasingly exploited (cf. Walling, 1998). Most attention has focussed on caesium-137 (\(^{137}\text{Cs}\)), and the successful use of this bomb-derived radionuclide in soil erosion studies has now been reported for many areas of the world (cf. Ritchie and McHenry, 1990; Walling, 1998). Caesium-137 measurements have been shown to provide an effective means of assembling spatially distributed, retrospective estimates of medium-term soil redistribution rates on the basis of a single site visit (e.g. Loughran et al., 1993; Walling and Quine, 1995; Walling, 2002). Use of the caesium-137 technique does, however, also involve a number of uncertainties (Walling, 1998), and it is important that these should be addressed, if it is to be used more widely and adopted as a tool for routine monitoring, as distinct from research investigations. What is arguably the greatest uncertainty relates to the need for a reliable procedure for converting measurements of the loss or gain of \(^{137}\text{Cs}\), relative to the local reference inventory, to a quantitative estimate of the medium-term net soil redistribution rate for the sampling point. Walling and Quine (1990) usefully reviewed this area of uncertainty more than a decade ago and highlighted the many inconsistencies and limitations in the ‘calibration’ or ‘conversion’ procedures that had previously been used by different workers.

In the absence of appropriate empirical relationships between the loss or gain of \(^{137}\text{Cs}\) and the soil redistribution rate, most studies have made use of theoretical conversion models. These models use existing understanding of the behaviour of \(^{137}\text{Cs}\) in an eroding or aggrading soil to formulate a model which enables an estimate of the soil redistribution rate to be derived from the value of loss or gain in \(^{137}\text{Cs}\) inventory, relative to the local reference inventory, calculated for the sampling point. In a recent paper, Walling and He (1999) provided details of a number of improved conversion models developed for this purpose and the same authors (Walling and He, 2001) have produced simple software for applying these models within the framework of two recent International Atomic Energy Authority (IAEA) Coordinated Research Projects (CRPs) aimed at promoting the application of environmental radionuclide tracers in soil erosion and sedimentation investigations. The availability of clearly documented conversion models and of standardised software for their implementation reduces the potential for inconsistency and problems associated with this aspect of the \(^{137}\text{Cs}\) technique, but uncertainties nevertheless remain. These uncertainties relate primarily to the lack of empirical validation of both the estimates of soil loss generated by the conversion models and the process-based assumptions incorporated within the models.

In a recent paper, Porto et al. (2001) provided an empirical validation of the estimates of soil erosion rates obtained for a small (1.38 ha) catchment in Calabria, southern Italy using \(^{137}\text{Cs}\) measurements. In this case, the catchment was uncultivated (largely forested) and a simple profile distribution model applicable to uncultivated soils was used to derive estimates of the soil redistribution rate for individual sampling points. Since there was little evidence of sediment deposition within the catchment and the sediment delivery ratio for
the catchment could therefore be assumed to be close to 100%, the mean rate of soil loss from the catchment surface, estimated using $^{137}$Cs measurements, could be directly compared with the sediment output from the catchment measured over a 17-year period. Close agreement between the two values served to validate the estimates of soil loss rates provided by the $^{137}$Cs measurements. Opportunities of this nature for empirical validation of the estimates of soil erosion rates provided by $^{137}$Cs measurements are, however, likely to prove rare, since direct comparison of estimates of soil loss for a small catchment with the measured sediment output is only possible when the sediment delivery ratio is close to 100%. Where significant deposition occurs, it is necessary to derive an estimate of the net soil loss from the catchment from the $^{137}$Cs measurements for comparison with the measured sediment yield. However, this comparison cannot provide a definitive validation of the estimates of soil erosion rates derived from $^{137}$Cs measurements, since overestimation of the erosion rates could be balanced by overestimation of deposition rates and vice versa.

In the absence of direct validation of the theoretical conversion models frequently used to obtain estimates of soil redistribution rates for cultivated areas, it is important to validate the process-based assumptions incorporated into such models. There have been few attempts to undertake such validation, and, interestingly, even the basic assumption that erosion or deposition of soil will be directly reflected by changes in the $^{137}$Cs inventory, due to removal or addition of sediment-associated $^{137}$Cs, has rarely been tested. In seeking to justify this basic assumption, reference is frequently made to the early work of Rogowski and Tamura (1965), who used plot studies to show that post fallout redistribution of $^{137}$Cs was primarily associated with soil erosion and sediment redistribution, and to the work of Ritchie et al. (1974), who reported a well-defined relationship between the percentage reduction in the $^{137}$Cs inventory associated with the soils of a number of long-term erosion plots and small watersheds in the USA and the rate of soil loss from those plots or small watersheds. Other plot studies, including that reported by Kachanowski (1987), have focussed on validating the $^{137}$Cs technique by relating the reduction in the $^{137}$Cs inventories associated with one or more plots to the measured rates of soil loss from those plots, rather than studying the actual loss of $^{137}$Cs in association with the eroded soil. Notable exceptions are the work of Loughran and Campbell (1995) and Dalgleish and Foster (1996). Loughran and Campbell (1995) measured the $^{137}$Cs content of soil eroded from three small (2 m$^2$) plots in the Maluna catchment, NSW, and established well-defined linear relationships between $^{137}$Cs loss and soil loss. Dalgleish and Foster (1996) reported experiments on a small laboratory plot using a rainfall simulator that confirmed that most of the $^{137}$Cs applied to the soil in the artificial rainfall was adsorbed by the soil and that its subsequent fate was controlled primarily by erosion of the surface soil. However, there was evidence that some of the $^{137}$Cs input was adsorbed by the mobilised sediment and the $^{137}$Cs content of the eroded soil was therefore significantly greater than that of the surface soil. To the authors’ knowledge, however, more detailed field-based investigations of the relationship between $^{137}$Cs and soil loss from cultivated soils are lacking. This paper presents the results of a study of $^{137}$Cs and soil loss from a series of experimental plots in southern Italy aimed at addressing the need for further empirical validation of the assumptions underlying the theoretical conversion models.
commonly used to derive estimates of soil redistribution rates from $^{137}$Cs measurements undertaken on cultivated land.

2. The experimental plots

The experimental plots used in the study are located on the northern side of the Torrent Menga valley near Gallina di Reggio Calabria in southern Italy (Fig. 1). The site is south facing and lies at an altitude of approximately 250 m above sea level. The underlying lithology is predominantly granite, with some quartzites and carbonates, and the soils have been classified as sandy-loams (USDA SCS, 1984). Representative values for the main soil properties are presented in Table 1. The climate of the area is typically Mediterranean, with a mean annual precipitation of ca. 600 mm, most of which falls during the period October to March. A summary of the longer-term average monthly climatic data for two nearby meteorological stations operated by the Aeronautica Militare is provided in Table 2. The soils of the area have not been cultivated during the last decade and support a natural cover of “macchia”, composed of grass and shrubs with an average height ranging from 10 to 50 cm. The canopy cover ranges from 70% to 95% and is almost uniform over the area.

In 1991, the University of Reggio Calabria established nine experimental plots at the site in order to monitor runoff and soil erosion under different slope and vegetation conditions (Fig. 2). The plots were aligned with their long axes following the line of steepest slope, and they are characterised by different lengths and slope angles. The three longer (33 m) plots have a 9% slope, whereas three of the six shorter (22 m) plots have a 9% slope and three an 18% slope. A bulldozer was used to grade the plots in order to
obtain the required slope angles and to produce a uniform plot surface, and in places, the soils were disturbed to depths of up to 30–40 cm. A sheet metal cutoff wall extending 30 cm into the soil and protruding 20 cm above the ground surface was installed around the upper and the two adjacent sides of each plot in order to isolate the plots hydrologically. On the lower side of each plot, troughs were installed to intercept the runoff and sediment output and to direct this to a 1-m³ storage tank. After construction, the plots were allowed to revegetate naturally and this vegetation cover has been maintained to date with periodic cutting. In the future, the plots will be subject to different cultivation and cropping practices.

Precipitation has been recorded at the site since 1990 using a tipping bucket rain gauge, but measurements of runoff and sediment loss from the plots have only been undertaken since January 2001. After each storm event, the sediment load collected in the tank is well mixed and several 1-L suspended sediment samples are collected from different depths within the tank. The sediment concentrations associated with these samples are determined by oven drying at 105 °C, and the mean sediment concentration of the samples is calculated. The sediment yield from each plot for each event is then calculated as the product of the mean sediment concentration and the water volume measured in the tank.

Table 1
Properties of the soils found within the study plots

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Depth (cm)</th>
<th>0–20</th>
<th>20–40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand (%)</td>
<td></td>
<td>58–88</td>
<td>60–87</td>
</tr>
<tr>
<td>Silt (%)</td>
<td></td>
<td>4–14</td>
<td>5–13</td>
</tr>
<tr>
<td>Clay (%)</td>
<td></td>
<td>8–27</td>
<td>8–27</td>
</tr>
<tr>
<td>Organic matter (%)</td>
<td></td>
<td>0.8–1.61</td>
<td>0.38–1.31</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>6.8–8.6</td>
<td>6.7–8.7</td>
</tr>
<tr>
<td>N_TOT (%)</td>
<td></td>
<td>0.42–1.12</td>
<td>0.26–0.90</td>
</tr>
</tbody>
</table>

Table 2
Mean monthly climate statistics for the study site

<table>
<thead>
<tr>
<th>Month</th>
<th>Rainfall (mm)</th>
<th>Rain days (no.)</th>
<th>Temperature (°C)</th>
<th>Rel. humidity (%)</th>
<th>Wind (km h⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JAN</td>
<td>88</td>
<td>14</td>
<td>11.5</td>
<td>72</td>
<td>13.5</td>
</tr>
<tr>
<td>FEB</td>
<td>67</td>
<td>11</td>
<td>11.5</td>
<td>71</td>
<td>14.9</td>
</tr>
<tr>
<td>MAR</td>
<td>43</td>
<td>10</td>
<td>13.0</td>
<td>69</td>
<td>16.1</td>
</tr>
<tr>
<td>APR</td>
<td>44</td>
<td>7</td>
<td>15.0</td>
<td>68</td>
<td>20.7</td>
</tr>
<tr>
<td>MAY</td>
<td>28</td>
<td>5</td>
<td>19.5</td>
<td>67</td>
<td>16.5</td>
</tr>
<tr>
<td>JUN</td>
<td>10</td>
<td>2</td>
<td>23.0</td>
<td>66</td>
<td>20.6</td>
</tr>
<tr>
<td>JUL</td>
<td>14</td>
<td>2</td>
<td>26.5</td>
<td>64</td>
<td>22.3</td>
</tr>
<tr>
<td>AUG</td>
<td>8</td>
<td>2</td>
<td>26.5</td>
<td>67</td>
<td>21.8</td>
</tr>
<tr>
<td>SEP</td>
<td>57</td>
<td>5</td>
<td>23.5</td>
<td>70</td>
<td>18.6</td>
</tr>
<tr>
<td>OCT</td>
<td>62</td>
<td>10</td>
<td>20.0</td>
<td>72</td>
<td>13.2</td>
</tr>
<tr>
<td>NOV</td>
<td>68</td>
<td>11</td>
<td>16.0</td>
<td>71</td>
<td>14.6</td>
</tr>
<tr>
<td>DEC</td>
<td>94</td>
<td>12</td>
<td>13.5</td>
<td>72</td>
<td>12.3</td>
</tr>
</tbody>
</table>
For each event, representative samples of the sediment recovered from the tanks were also retained for subsequent $^{137}$Cs analysis.

### 3. Soil sampling and $^{137}$Cs analysis

Collection of soil samples from the experimental plots for $^{137}$Cs analysis involved two separate coring exercises. The first, which was viewed as a reconnaissance sampling campaign, aimed to investigate the effects of the bulldozing operations undertaken in 1991 on the $^{137}$Cs inventories and depth distributions associated with the soils of the plots. This involved collection of soil cores from two parallel downslope transects established within two of the plots (plots 3 and 6). A total of 22 bulk cores were collected from the two plots (see Fig. 3) to a depth of ca. 75 cm, using a steel core tube (internal diameter 6.9 cm) driven into the ground by a motorised percussion corer and subsequently extracted using a hand-operated winch. In order to document the depth distribution of $^{137}$Cs in the soil profile, six depth incremental profiles (see Fig. 3) were also collected within the same plots, using a 650-cm$^2$ surface area scraper plate sampler (Campbell et al., 1988). The same sampler was used to establish the local reference inventory by collecting two additional sectioned profiles from an area of permanent grassland with minimum slope adjacent to the study plots.

The second sampling campaign was undertaken to provide samples of surface soil from each of the plots, for use in a comparison of the $^{137}$Cs content of surface soil with that of the sediment collected in the tanks at the outlet of each plot. All plots were sampled at the
top, middle and bottom (cf. Fig. 2), and a total of 27 surface soil samples (i.e. 3 per plot) were collected to a depth of 2 cm using the scraper plate sampler referred to above. The bulk soil cores, the depth incremental samples, the samples of surface soil and the samples of sediment collected from the tanks were transported to the laboratory of the Department of Geography at the University of Exeter, UK, for processing and analysis. All samples were initially oven-dried at 45 °C, mechanically disaggregated and passed through a 2-mm sieve. A representative fraction of each sample (<2 mm) was then placed into a plastic pot or Marinelli beaker (according to sample size) for determination of its 137Cs activity. Cs-137 concentrations were measured by gamma spectrometry at 662 keV, using a high-resolution coaxial HPGe p-type detector coupled to a PC-based data collection system. Count times were typically ca. 30,000 s, providing results with an analytical precision of ca. ±10% at the 95% level of confidence.

In addition, the absolute grain size composition of the <2 mm fraction of each sample was determined using a Malvern Mastersizer MS 20 laser granulometer, following pretreatment with hydrogen peroxide to remove the organic component and chemical dispersion with sodium hexametaphosphate. The specific surface area (SSA) of each sample (m² g⁻¹) was estimated from its absolute grain size distribution, assuming spherical particles. This measure has been shown to provide a useful index of the grain

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Fig. 3. The location of the bulk cores and sectioned profiles collected from plots 3 and 6.
size composition, when examining the relationship between the grain size composition of a sample and its $^{137}$Cs content (cf. He and Walling, 1996).

4. Results

4.1. The distribution of $^{137}$Cs within the experimental plots and the adjacent area

The $^{137}$Cs inventories associated with the two sectioned profiles collected from the reference site located adjacent to the study plots were 2033 and 2088 Bq m$^{-2}$, respectively. The $^{137}$Cs depth distributions associated with these sites are depicted in Fig. 4, with depth expressed as the cumulative mass depth. Both profiles show evidence of cultivation since the main period of bomb fallout (i.e. 1956–1970) and prior to the past decade when the area was left uncultivated. Cs-137 is seen to be well mixed through the plough layer (top ca. 15–20 cm), and the profiles conform to the depth distribution expected for cultivated soils (cf. Walling and Quine, 1995; He and Walling, 1997).

The values of $^{137}$Cs inventory obtained for the 22 bulk cores collected from plots 3 and 6 ranged from 153 to 3467 Bq m$^{-2}$, and therefore provide evidence of both loss and gain of $^{137}$Cs, relative to the inventories obtained for the two reference sites. The patterns shown by the $^{137}$Cs inventories within the two plots, represented using a kriging interpolation procedure, are illustrated in Fig. 5. The two plots show broadly similar patterns, with reduced $^{137}$Cs inventories within the upper parts of the plots and...
accumulation of $^{137}\text{Cs}$ towards the bottoms of the plots. Details of the $^{137}\text{Cs}$ depth distributions associated with this pattern are provided by Fig. 6, which presents the depth distributions obtained for the depth incremental samples collected from the upper, middle and lower parts of plot 3. The equivalent results for plot 6 were similar. When compared with the $^{137}\text{Cs}$ depth distributions shown for the reference sites in Fig. 4, the $^{137}\text{Cs}$ depth profiles of both plots were found to be truncated in the upper and middle parts of the plots and extended towards their lower boundaries. Both the spatial distribution of $^{137}\text{Cs}$ inventories within plots 3 and 6 presented in Fig. 5 and the associated variation of the $^{137}\text{Cs}$ depth distribution illustrated in Fig. 6 are consistent with the erosional redistribution of $^{137}\text{Cs}$ that might be expected to occur within an erosion plot (i.e. erosion and associated
removal of $^{137}\text{Cs}$ in the upper and middle parts of the plot and deposition and associated accumulation of $^{137}\text{Cs}$ at the base of the plot). The limited extent of the depositional areas at the bottoms of the plots, indicated by the distributions of $^{137}\text{Cs}$ inventories shown in Fig. 5, is again consistent with expectations, since there would be only limited opportunity for deposition at the foot of an essentially uniform rectilinear slope. However, in view of the short period elapsed since the experimental plots were constructed in January 1991 (i.e. 10 years) and thus the limited opportunity for erosional redistribution of soil within the plots, it seems likely that the spatial patterns and depth distributions shown in Figs. 5 and 6 also reflect the earthmoving associated with the construction of the plots. The need to grade the slopes of the plots could have resulted in removal of soil from the upper parts of the plots and transfer of this soil to the lower part of the plots. The peak in $^{137}\text{Cs}$ activity found towards the base of the $^{137}\text{Cs}$ depth distribution illustrated in Fig. 6C could thus reflect the burial of a preexisting $^{137}\text{Cs}$ profile by soil transferred from upslope by the bulldozer and, equally, the truncation of the $^{137}\text{Cs}$ profiles in the upper part of the plots could reflect removal of the surface layer from the preexisting $^{137}\text{Cs}$ profile during earthmoving.

The relative importance of water-induced erosion, transport and deposition (both prior to, and after, construction of the plots) and the earthmoving associated with the installation of the experimental plots in 1991, in influencing the $^{137}\text{Cs}$ inventories now found on the plots, is uncertain. This therefore precludes the use of these inventories to estimate the rates of soil loss associated with the plots. However, the results presented above were seen as demonstrating that both the spatial and vertical distributions of $^{137}\text{Cs}$ within the soils of the experimental plots were consistent with those that might be expected of eroding agricultural soils and thus that the experimental plots would afford a meaningful and effective basis for investigating the erosional behaviour of $^{137}\text{Cs}$ and for validating some of the assumptions associated with conversion models commonly employed when using $^{137}\text{Cs}$ measurements to estimate erosion and soil redistribution rates on cultivated soils.

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**Fig. 6.** The $^{137}\text{Cs}$ depth distributions associated with the three sectioned profiles collected from plot 3.
4.2. Sediment outputs from the experimental plots

Measurements of sediment output were obtained from each individual plot for 16 events that occurred during the period extending from January 2001 to September 2002. The rainfall totals associated with these events are shown in Fig. 7A, and Fig. 7B provides information on the sediment outputs from each of the plots for the 16 events. Fig. 7B indicates that the first three events of 2001 accounted for ca. 75% of the annual sediment

Fig. 7. Rainfall amounts (A) and sediment outputs from the nine plots (B and C) for the 16 storm events that occurred between January 2000 and September 2002.
output from the plots for that year. This partly reflects the relatively high rainfall totals associated with the first and third events, which occurred in January and April 2001. However, it may also point to the existence of a seasonal exhaustion effect (cf. Walling and Webb, 1982) or the influence of the reduced antecedent moisture levels associated with events occurring during the drier months of the spring and summer in reducing runoff and erosion during these months. The cumulative soil loss for the individual plots associated with the 16 events that occurred during the 21-month study period ranged from 0.13 to 0.57 t ha\(^{-1}\). Such values must be seen as relatively low since there were relatively few major storm events during the study period.

4.3. The particle size composition of eroded soil

Information on the ultimate or primary grain size distributions of the sediment eroded during the individual events and the mean grain size distribution of the surface soil for the individual plots is provided in Fig. 8, which portrays the spread of the particle size distributions derived for the eroded sediment around that of the surface soil. The mean grain size distribution of the surface soil is based on the three samples collected from the surface of each plot. For the majority of the plots (i.e. plots 1, 2, 3, 5, 6, 8 and 9), the eroded soil has a similar grain size composition to the surface soil, being slightly coarser for some events and slightly finer for others. However, for two of the nine plots (i.e. plots 4 and 7), the size distribution of the sediment eroded from the plots is consistently coarser than that of the surface soil. Some of the differences between the particle size distributions of the eroded soil and the surface soil evident in Fig. 8 are likely to reflect spatial variability of the grain size composition of the surface soil within the plot and thus sampling variability associated with the small number of soil samples collected (i.e. three). A more general tendency for the eroded soil to be depleted in fines is evident from Fig. 9, which compares the frequency distribution of specific surface area (SSA) values obtained for the samples of eroded soil \((n = 140)\) with those of the samples of surface soil collected from the plot \((n = 27)\). The values of SSA are consistently lower for the eroded soil.

Although it is frequently assumed that eroded soil will be enriched in fines, relative to the source material, due to preferential mobilisation of the finer particles (cf. Stone and Walling, 1997), there are many studies reported in the literature where the eroded soil is coarser than the surface soil (cf. Young, 1980). Findings similar to those encountered in this investigation were reported by Young and Onstad (1978) for loam, silt loam and loamy sand soils in Minnesota, USA. These authors distinguished soil eroded from rill and interrill areas and compared the primary grain size distributions of sediment eroded from rill and interrill areas with those of the bulk surface soil. They found that soil eroded from interrill areas had a higher sand content and a lower clay content than the bulk soil and the sediment eroded from rills. They suggested that these contrasts could reflect the transport processes involved. In the case of interrill areas, the primary transport process is rainsplash, which is capable of transporting larger particles. Since much of the soil mobilised by splash erosion will be in the form of aggregates, the primary size distribution of the eroded soil will reflect the size and composition of the eroded aggregates. Available observations indicate that interrill processes dominate sediment mobilisation and transport.
on the plots investigated in this study, and the general enrichment of the eroded soil in the coarser size fractions and its depletion in fines is consistent with the findings of Young and Onstad (1978) cited above.

4.4. The relationship between $^{137}$Cs loss and soil loss

The relationships between $^{137}$Cs loss ($Y_i$, Bq m$^{-2}$) and soil loss ($X_i$, kg m$^{-2}$) for the 16 events are shown for each of the nine plots in Fig. 10. In all cases, there is clear positive relationship of the form:

$$Y_i = aX_i^b$$

(1)
indicating that $^{137}$Cs loss and soil loss are very closely related. The relatively small number of events available precludes precise statistical fitting of this equation, but the simplified equation

$$Y_i = aX_i^{1.0}$$

has been fitted to each of the datasets by least squares and the lines representing the resulting function have been superimposed on the data plots in Fig. 10. The visual fits suggest that Eq. (2) provides an effective representation of the relationship, and this is further confirmed by the $r^2$ values for the individual datasets, which range between 0.59 and 0.90 and are significant at the >99% level. These results suggest that the $^{137}$Cs concentrations in the eroded sediment remain relatively constant between events and that there is no clear trend for $^{137}$Cs concentrations to increase (i.e. $b>1.0$) or decrease (i.e. $b<1.0$) as the magnitude of the soil loss ($X_i$) increases. This was further confirmed by correlating the values of $^{137}$Cs concentration and soil loss, associated with the individual events, for each plot. In all cases, there was no statistically significant correlation. The magnitude of the constant $a$ in Eqs. (1) and (2) could be expected to vary according to the condition of the plot, and particularly in response to the magnitude of past erosion rates, since higher erosion rates will have removed a greater proportion of the $^{137}$Cs inventory and will thus result in lower $^{137}$Cs concentrations in the tillage horizon. In addition, the value of $a$ would be sensitive to any contrasts between the plots in terms of grain size selectivity of soil loss. For this study site, however, the constant $a$ appears to vary relatively little between the individual experimental plots, which have been subject to similar treatment since their construction, and a single relationship of the form represented by Eq. (1) (i.e. $Y_i = 4.0162X_i^{0.99}$, $r^2 = 0.75$, significant at >99% level) has been fitted by least squares regression to the combined dataset from all
plots in Fig. 11. An equivalent relationship has been fitted to the values of total $^{137}$Cs loss and total soil loss from the nine plots for the 16 events in Fig. 12. The resulting equation (i.e. $Y = 5.15X^{1.05}, r^2 = 0.89$, significant at >99% level) has similar values for both the constant and the exponent, further emphasising the relatively constant values of $^{137}$Cs concentration associated with both the individual plots and the individual events. Similar power function relationships between $^{137}$Cs loss and soil loss and vice versa have been reported by other workers (e.g. Rogowski and Tamura, 1970; Ritchie et al., 1974; Campbell et al., 1986), using both event and annual data for erosion plots. However, in the case of the plot experiments reported by Loughran and Campbell (1995), referred to above, there was considerably more variation in the form of the relationship between $^{137}$Cs loss and soil loss for the individual plots. This variation could reflect the uncultivated nature of the soils on which the plots were installed and marked contrasts in soil type between the plots.

Fig. 10. The relationship between $^{137}$Cs loss and soil loss for the events monitored on the individual plots. The fitted line represents the simple function $Y_i = aX_i^{1.0}$ (Eq. (2)). Best-fit values for the constant $a$ are provided for each plot.
Fig. 11. The relationship between $^{137}$Cs loss and soil loss for the combined dataset from all plots. The fitted regression line takes the form of Eq. (1).

$Y = 4.0162X^{0.98}$

Fig. 12. The relationship between total $^{137}$Cs loss and total soil loss from the individual plots for the 16 monitored storm events.

$Y = 5.15X^{1.05}$
4.5. The relationship between $^{137}$Cs concentrations in mobilised sediment and surface soil

The relationship between the $^{137}$Cs content of mobilised sediment and that in the soil is shown in Fig. 13A, which plots the mean $^{137}$Cs content of the sediment lost from each plot.
during the 16 individual events versus the mean $^{137}$Cs content of the surface soil from the respective plot. Although the lack of a significant relationship between the $^{137}$Cs content of the soil eroded by individual events and the magnitude of the soil loss associated with those events has already been identified, Fig. 13A, nevertheless, demonstrates that the $^{137}$Cs content of the eroded sediment does vary between events. This plot is further summarised in Fig. 12B, which presents the relationship between the load-weighted average values of $^{137}$Cs concentration for the sediment lost from the individual plots and the mean $^{137}$Cs concentration of the surface soil from the individual plots. Both relationships demonstrate that the $^{137}$Cs content of the mobilised sediment is similar to that of the surface soil, although, in most cases, it is lower. This situation is consistent with the results outlined above, which indicate that the eroded sediment is frequently coarser than the parent soil (cf. Figs. 8 and 9), since it is well known that $^{137}$Cs is preferentially associated with the finer fractions of soil and sediment samples (cf. Livens and Baxter, 1988; Walling and Woodward, 1992; He and Walling, 1996).

5. Discussion

The results presented in Fig. 10 confirm the basic assumption of the $^{137}$Cs technique that removal of soil from a soil profile by erosion is associated with removal of $^{137}$Cs and thus a reduction in the $^{137}$Cs inventory. In this study, a simple linear relationship (i.e. $Y_i = aX_i^{1.0}$ or $Y_i = aX_i$) between $^{137}$Cs loss ($Y$, Bq m$^{-2}$) and soil loss ($X$, kg m$^{-2}$) was found to be appropriate for the measurements obtained for the 16 events from each of the plots. This is again consistent with the assumptions of the $^{137}$Cs technique since the soil cores collected from the plots (Fig. 6) demonstrated that the $^{137}$Cs was well mixed in the upper part of the soil and, in the absence of any accumulation of fresh $^{137}$Cs fallout at the soil surface, the $^{137}$Cs content of the eroded soil could be expected to be largely independent of the magnitude of the soil loss associated with a specific event. As indicated previously, variations in the constant $a$ in the relationship $Y_i = aX_i$ will reflect both contrasts in the $^{137}$Cs content of the soils from the individual plots and differences between the plots in terms of the $^{137}$Cs content of the eroded sediment relative to that of the surface soil. The former will in turn reflect the erosional history of the plots and earthmoving associated with their construction, in that these will both influence the present levels of $^{137}$Cs in the surface soil of the individual plots. Under ‘natural’ conditions, the relationships presented in Fig. 10 could be expected to vary over time, since, as erosion proceeds, $^{137}$Cs will be lost from the soil and if the soil is regularly tilled, the concentrations in the plough layer will decline and thus the amount of $^{137}$Cs lost for a given value of soil loss would progressively decline and the value of $a$ would therefore become smaller.

The relationships presented in Fig. 13 demonstrate that the $^{137}$Cs content of eroded sediment is similar to that of the surface layers of the soil, thereby providing further confirmation of the close relationship between soil loss and $^{137}$Cs loss from the study plots. In most cases, however, the $^{137}$Cs content of the eroded soil is less than that of the surface soil, and Fig. 13B indicates that for seven out of the nine plots, the load-weighted mean concentration of the eroded soil is less than that of the surface soil. The maximum difference is associated with plot 7, where the load-weighted mean $^{137}$Cs concentration of
the eroded soil is only ca. 66% of that of the surface soil. The reduced $^{137}$Cs concentrations associated with the eroded sediment, relative to the surface soil, could reflect the preferential association of eroding areas on the plots with areas characterised by lower $^{137}$Cs concentrations, but, as indicated above, they are more likely to reflect contrasts in grain size composition between the eroded sediment and the surface soil, which in turn reflect contrasts in the grain-size selectivity of soil loss between individual plots (cf. Fig. 8).

Many workers have highlighted the need to take account of the grain size selectivity of erosion processes when using $^{137}$Cs measurements to estimate rates of soil redistribution, since contrasts in grain size composition of eroded sediment relative to the parent soil will influence its $^{137}$Cs content (e.g. Sutherland, 1991; Walling and Quine, 1990; Walling and He, 1999, 2001). Thus, if it is assumed that the $^{137}$Cs content of eroded soil is similar to that of the parent soil, but in fact it is considerably greater due to preferential mobilisation of the finer fractions, erosion rates will be overestimated. Equally, if the $^{137}$Cs content of eroded sediment is less than that of the parent soil due to preferential mobilisation of the coarser fractions, erosion rates will be underestimated.

He and Walling (1996) have suggested that such particle size effects can be incorporated into the conversion models used to estimate soil redistribution rates from $^{137}$Cs measurements by applying a correction factor $P$, defined as the ratio of the $^{137}$Cs concentration in the eroded sediment to that in the original source material. Since it is frequently impossible to establish the value of $P$ empirically, He and Walling (1996) further suggested that its value could be estimated from a comparison of the specific surface area of the sediment $SSA_{sed}$ and of the surface soil $SSA_{soil}$ using the equation

$$P = \left(\frac{SSA_{sed}}{SSA_{soil}}\right)^n$$

where $n$ is an exponent which assumes values ranging from 0.65 to 0.75. The data obtained from the study plots can be used to test the validity of Eq. (3) since the value of $P$ can be calculated for the individual samples of eroded sediment collected from the nine erosion plots.

The values of $P$ calculated for each of the samples collected from the individual plots using the mean value of $^{137}$Cs content for the surface soil within the plot have been plotted against equivalent values for the ratio of $SSA_{sed}$ to $SSA_{soil}$ in Fig. 14A. A line representing the relationship between $P$ and the ratio of $SSA_{sed}$ to $SSA_{soil}$ proposed by He and Walling (1996) (cf. Eq. (3), $n = 0.65$) has been superimposed on the resulting plot. Fig. 14A provides some evidence of a positive relationship between $P$ and the ratio of $SSA_{sed}$ to $SSA_{soil}$ of the form proposed by He and Walling (1996), but it is clear that the magnitude of $P$ is influenced by other factors, apart from the specific surface area ratio. This is further demonstrated in Fig. 14B which plots the relationship between the $^{137}$Cs enrichment ratios estimated from the ratio of $SSA_{sed}$ to $SSA_{soil}$ using Eq. (3) ($n = 0.65$) and the values based on the measured $^{137}$Cs concentrations.

In using a conversion model, any particle size correction factor is likely to be applied as a lumped or average value within the model. In order to represent this situation more closely, the event-based data presented in Fig. 14 have been averaged to provide load-
weighted mean values of the $^{137}$Cs enrichment ratio ($P$) and the specific surface area ratio. The relationship between these two values for the nine plots is presented in Fig. 15A, along with the relationship between the estimated and measured $^{137}$Cs enrichment ratios (Fig. 15B). Fig. 15, which is based on load-weighted average values, can therefore be
directly compared with Fig. 14, which is based on the event data. Fig. 15 suggests that the particle size correction factor proposed by He and Walling (1996) affords an initial basis for taking account of particle size effects when applying a conversion model, but again
emphasises that further work is required to provide a more precise means of taking account
of particle size effects.

6. Conclusion

The use of $^{137}\text{Cs}$ measurements to obtain information on soil erosion and deposition
rates depends very heavily on the validity of the conversion or calibration models used to
derive an estimate of the soil redistribution rate from the measured reduction or increase in
the $^{137}\text{Cs}$ inventory, relative to the reference inventory. It is therefore important that
attention should be directed to confirming the validity of these models. In the absence of
reliable empirical conversion models, most studies have employed theoretical conversion
models that are based on various assumptions regarding the behaviour of $^{137}\text{Cs}$ in an
eroding soil. Most of these assumptions are based on existing understanding of the
interaction of radiocaesium with soils and sediments and the fate of radiocaesium fallout
arriving at the soil surface. However, there have been few attempts to validate these
theoretical conversion models either by comparing soil redistribution rates estimated using
$^{137}\text{Cs}$ measurements with independent measurements of those rates (cf. Porto et al., 2001)
or by testing the assumptions and process representations incorporated into the models.
This paper reports the results of an attempt to test some of the common assumptions
regarding the relationship between $^{137}\text{Cs}$ loss and soil loss from an eroding site. Use has
been made of event-based measurements of soil loss from nine small plots and associated
measurements of the $^{137}\text{Cs}$ content and grain size composition of the sediment lost from
the plots and of the soil within the plots.

The results presented in Figs. 10–12 provide a clear validation of the general
assumption that the magnitudes of $^{137}\text{Cs}$ and soil loss from an eroding site are closely
related and that measurement of the reduction in the $^{137}\text{Cs}$ inventory of an eroding site
should provide an effective basis for estimating the magnitude of the erosion rate. The
results presented in Fig. 13 similarly confirm that the $^{137}\text{Cs}$ content of the eroded sediment
is similar to that of the surface soil within the plots, although, in most cases, it is less. This
reduction in the $^{137}\text{Cs}$ content of the eroded sediment relative to the soil was shown to
reflect contrasts in grain size composition, thereby emphasising the need to incorporate the
size selectivity of erosion and deposition processes into conversion models. The procedure
advocated by He and Walling (1996) as a simplified means of predicting the impact of
contrasts in grain size composition between the eroded soil and the parent soil on their
relative $^{137}\text{Cs}$ contents was shown to afford an initial basis for establishing a particle size
correction factor, but further work is clearly required to develop and refine such
procedures.

Although these findings must be viewed as providing valuable confirmation of the
validity of several important assumptions associated with the theoretical conversion
models used to derive estimates of soil redistribution rates from $^{137}\text{Cs}$ measurements,
there are several other assumptions and uncertainties regarding the behaviour of $^{137}\text{Cs}$ in
an eroding soil which still require testing or elucidation. These include the fate of fresh
fallout to the soil surface, prior to its incorporation into the soil by cultivation, and the
impact of the precise nature of the erosion processes (i.e. the relative importance of rill and
sheet erosion) in influencing the relationship between $^{137}$Cs loss and soil loss from uncultivated soils. In such soils, the $^{137}$Cs concentration will frequently decline rapidly with depth and thus erosion of a given mass of soil could remove different amounts of $^{137}$Cs, according to whether the erosion processes were characterised by sheet erosion operating over the whole surface or rill erosion involving a small number of incised rills. The amount of $^{137}$Cs removed with a given mass of soil is likely to be considerably greater in the former, than in the latter, case. In the absence of significant $^{137}$Cs fallout at the present time, studies of the fate of fresh fallout clearly fall outside the scope of studies such as that presented here. Experimental investigations involving application of $^{137}$Cs to a plot surface, similar to those reported by Dalgleish and Foster (1996), would be required. Nevertheless, scope exists to investigate the significance of different erosion processes using more standard plot measurements, and it is to be hoped that such questions will be addressed by future work.

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