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Using fallout radionuclides to investigate erosion and sediment delivery: some recent advances

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Abstract Increasing concern for the offsite impacts of soil erosion and the effects of fine sediment in degrading aquatic habitats and ecosystems has produced new information requirements for sediment studies. There is a need for information on the internal functioning of the catchment, in terms of sediment sources, transfers, sinks and outputs and the catchment sediment budget. Sediment tracers, and particularly fallout radionuclides, provide an effective means of assembling such data and there is a need to combine traditional monitoring techniques with such tracing techniques. Fallout radionuclide tracers have now been successfully used for many years, but their potential remains to be fully realised. This contribution describes five areas in which advances have recently been made. These include the use of ^{137}Cs measurements to document the change in erosion rates caused by changes in land management, upscaling the ^{137}Cs approach to provide reconnaissance assessments of soil loss at the regional or national scale, improvement of existing approaches to the use of ^{7}Be, to permit consideration of longer periods, the conjunctive use of ^{137}Cs and ^{7}Be to assess the magnitude of recent changes in erosion rates and the use of Chernobyl fallout to provide an improved chronology for interpreting the sedimentary archives provided by overbank flood plain deposits.

Key words erosion; sediment delivery; fallout radionuclides; tracers; caesium-137; beryllium-7

INTRODUCTION

Growing concern for the offsite or downstream impacts of soil erosion and the effects of fine sediment in degrading aquatic habitats and ecosystems has directed attention to the need for sediment management in catchment and river basins (e.g. Owens, 2008). These developments have emphasised the limitations of traditional sediment monitoring programmes that commonly focus on documenting the sediment yield at a catchment outlet and the need for information on the internal functioning, and more particularly the sediment budget, of a catchment. A catchment sediment budget provides a valuable tool for understanding the internal functioning of a catchment and for informing the development of effective sediment management and control strategies (Walling & Collins, 2008). Walling (2006) has, however, drawn attention to an apparent paradox, whereby, although the need to assemble information on catchment sediment budgets is increasingly recognised, the tools to obtain such information are often lacking. Against this background, sediment tracing techniques can provide a valuable supplement and complement to more traditional monitoring procedures.

Tracing techniques are being increasingly used to provide an improved understanding of catchment sediment budgets, and two approaches may be highlighted as having proved particularly successful. The first is the use of sediment source tracing techniques to establish the relative importance of the potential sediment sources within a catchment (e.g. Walling, 2005; Collins & Walling, 2007), whilst the second is the use of fallout radionuclides to estimate rates of soil and sediment redistribution within a catchment and to provide a chronology for use in investigating sediment sinks (e.g. Zapata, 2002; Walling, 2003, 2006; Mabit *et al.*, 2008). Combination of these two approaches can frequently provide the information required to establish the framework for developing a sediment budget (Walling *et al.*, 2006). Fallout radionuclides have now been widely used in soil erosion and catchment sediment budget investigations in many different areas of the world (Ritchie & Ritchie, 2007; Mabit *et al.*, 2008) and although their use is in most instances still primarily linked to research oriented investigations, they are also being increasingly used within more routine investigations focused on informing and supporting catchment management. This contribution focuses on recent advances in the use of fallout radionuclides as sediment tracers.

Most work with fallout radionuclides has involved the use of caesium-137 (^{137}Cs). This artificial radionuclide derived from the atmospheric testing of nuclear weapons with a half-life of

30.17 years, has been widely used to document soil and sediment redistribution rates within catchments over a timescale of approx. 50 years, linked to the timing of the main period of "bomb" fallout, which extended from the mid 1950s to the 1970s. There have been numerous reports of the successful use of ^{137}Cs to document soil erosion rates on both cultivated and uncultivated land and to estimates rates of sediment accretion on river flood plains and other sediment sinks. Recent work has also demonstrated the potential for using unsupported lead-210 (^{210}Pb$_{ex}$) in a similar manner. In contrast to ^{137}Cs, ^{210}Pb$_{ex}$ is a natural geogenic radionuclide, although it again reaches the land surface as fallout. With a half-life of 22.3 years and an essentially continuous fallout input, ^{210}Pb$_{ex}$ provides a means of documenting soil and sediment redistribution rates over a timescale of approx. 100 years. The capacity of these two radionuclides to provide information on the functioning of catchment sediment budgets over timescales of approx. 50–100 years, represents an important strength, in that it overcomes many of the problems associated with attempting to document the operation of processes characterized by a high degree of inter-annual variability. However, in other contexts, the medium-term nature of the estimates of soil and sediment redistribution rates provided by these two radionuclides represents a disadvantage, in that there is also often a need to document changes or trends within the period of interest; for example in response to land use change. To meet this need, increasing attention has been directed to the potential for using beryllium-7 (^{7}Be), a short-lived natural cosmogenic radionuclide with a very much shorter half-life of 53 days, to document soil and sediment redistribution associated with individual high magnitude events or a group of events covering a relatively short period

Although most studies involving fallout radionuclides undertaken to date have focused on one particular radionuclide, attention has also begun to be directed to the potential for combining information from two or perhaps more radionuclides, to provide information relating to different timescales, which can provide a basis for evaluating the erosional history of an area or the changing sediment budget of a catchment. Walling *et al.* (2003), for example, report how it proved possible to use both ^{137}Cs and ^{210}Pb$_{ex}$ measurements to document changes in the sediment budget of the small 63-km^2 Kaleya catchment in Zambia over the past approx. 100 years, in response to changing land use and population pressure and the introduction of soil conservation measures.

Another key feature of most work employing fallout radionuclides as tracers undertaken to date is the emphasis on relatively small areas. Many studies have focused on individual fields and have provided detailed information on the rates and patterns of soil redistribution within small areas. However, there are many instances in soil erosion and sediment budget investigations where information on larger areas is required, particularly for informing policy and the development of effective soil erosion and sediment management programmes. This requirement for what could be viewed as reconnaissance scale information has encouraged attempts to upscale the application of fallout radionuclides to larger areas, by using data extrapolation and interpolation techniques to extend the data collected from small areas or representative parts of a catchment to much larger areas. Mabit *et al.* (2007) report such a study, where ^{137}Cs measurements made within representative areas were used to develop a sediment budget for the 217-km^2 Boyer catchment in Quebec, Canada.

This contribution aims to provide examples of recent work in extending existing approaches to the use of fallout radionuclides in soil erosion and sediment budget investigations through the development of new approaches or exploiting new opportunities. These include, firstly, the use of ^{137}Cs measurements to assess the impact of changing land management practices on soil erosion rates, secondly, the use of ^{137}Cs measurements to undertake a national scale soil erosion survey, thirdly, the development of procedures which permit ^{7}Be measurements to be used to estimate soil redistribution rates over much longer periods than previously studied, fourthly, the conjunctive use of ^{7}Be and ^{137}Cs measurements to assess the impact of recent changes in land use in increasing erosion rates, and, finally, the use of ^{137}Cs measurements in areas with significant inputs of Chernobyl fallout to provide improved chronologies for interpreting the sediment archives provided by flood plain sediment cores. In all cases, it is only feasible to provide an overview of the new approaches and developments, but reference is made to several publications, which provide a more detailed description of the approach employed.

USING ^{137}Cs MEASUREMENTS TO DOCUMENT THE IMPACT OF A CHANGE IN LAND MANAGEMENT ON SOIL EROSION RATES

The basis

The traditional use of ^{137}Cs measurements to document soil redistribution rates provides information on average rates over the past approx. 50 years, and assumes that soil condition and tillage practices, and therefore erosion rates, have remained essentially stationary over that period. A substantive change in land use or land management during this period could violate key assumptions and invalidate the approach. However, where such changes have occurred, information on the change in the magnitude of the erosion rate will frequently be needed. Where this change occurs approximately half way through the 50-year period, extending from the onset of bomb fallout (t_1, year) to the present (t_3, year), i.e. at t_2, year, and the change involves a shift from cultivation to non-cultivation, scope may exist to use ^{137}Cs measurements to quantify the erosion rates associated with both periods and to thus assess the magnitude of any change in erosion rates between the two periods. Such situations could, for example, exist where land abandonment causes a shift from cultivation to fallow conditions or where no-till practices are introduced to reduce the rates of soil loss associated with conventional tillage. In these situations, the first period (Period A) when cultivation occurs, can be expected to result in the creation of a well-mixed plough layer characterized by a near homogeneous ^{137}Cs mass activity density and bulk density. Ongoing erosion and incorporation of soil from below the plough depth to maintain the thickness of the plough layer will result in a progressive dilution of the ^{137}Cs activity in the plough layer. With the cessation of cultivation, the ^{137}Cs mass activity density in the plough layer will remain essentially unchanged, apart from the reduction associated with radioactive decay. However, erosion or deposition occurring during the second period (Period B) will reduce or increase the depth of the original plough layer, respectively, and thus the depth to which ^{137}Cs is found.

Considering the situation at t_3, an estimate of the mean annual erosion ($R_B < 0$) or deposition rate ($R_B > 0$) (kg m^{-2} year^{-1}) associated with the second period (Period B) can be obtained by establishing the current mass depth of the plough layer (h_{t3}, kg m^{-2}) and comparing this with the plough depth (H, kg m^{-2}) for the cultivation associated with the first period viz.

$$R_B = \frac{h_{t3} - H}{t_3 - t_2} \tag{1}$$

Since establishing the depth of the plough layer for a number of sampling points by direct measurement is likely to prove a time-consuming task, due to the need to document the ^{137}Cs depth distribution, to define the base of the zone of homogeneous ^{137}Cs activity, an alternative and simpler method can be employed. For this, two samples are collected from each sampling point. The first, a bulk core that extends below the depth of the plough layer containing ^{137}Cs, is used to establish the ^{137}Cs inventory (A_{t3}, Bq m^{-2}) at the sampling point. The second, a shallow core is used to determine the current ^{137}Cs mass activity density (C_{t3}, Bq kg^{-1}) of the plough layer. If it is assumed that the total ^{137}Cs inventory (A_{t3}, Bq m^{-2}) is contained within the zone of homogeneous ^{137}Cs activity represented by the plough layer, the mass depth of that layer (h_{t3}, kg m^{-2}) at the sampling point can be estimated by dividing the total ^{137}Cs inventory at the sampling point by the ^{137}Cs mass activity density (C_{t3}). In most environments, a small proportion of the total ^{137}Cs inventory contained in the soil will be found below the base of the plough layer (e.g. approx. 5%), due to slow downward migration and an empirical reduction/correction factor can be determined and applied to A_{t3} to take this into account.

For Period A, an estimate of the ^{137}Cs inventory at a sampling point at the end of the period (A_{t2}, Bq m^{-2}) can be obtained by taking the current inventory (A_{t3}), increasing or reducing this to take account of the change in the depth of the zone of homogeneous mixing previously estimated for Period B and adjusting the result to take account of radioactive decay between t_2 and t_3 viz:

$$A_{t2} = \left[A_{t3} - \{h_{t3} - H\}C_{t3}\right]\exp\left[Ln(2)(t_3 - t_2 / T_{1/2})\right] \tag{2}$$

where $T_{1/2}$ is the half life (years) of ^{137}Cs. Alternatively, A_{t2} could be estimated as the product of H and C_{t3}, again taking account of radioactive decay. The estimate of A_{t2} can be used to obtain the mean annual erosion rate during Period A (R_A), (kg m^{-2} year^{-1}) by comparison with an estimate of the reference inventory for the study site at t_2, using one of the conversion models described by Walling & He (1999).

Investigating the change in soil erosion rates associated with a shift from conventional tillage to a no-till system on agricultural land in Chile

The intensification of agriculture for cereal production after 1970 resulted in greatly increased rates of soil loss in the Coastal Mountains of south-central Chile. The system of conventional tillage with burning of crop residues (CT) resulted in erosion rates described as being amongst the highest for any agricultural land in Chile. Concern for both loss of productivity and the downstream impacts of increased sediment inputs to local water courses and river systems resulted in a shift from CT to a system involving no-till management without burning of the crop residues (NT). The implementation of NT has been reported to have resulted in improved soil quality but uncertainties remain as to the extent to which erosion rates have been reduced. The approach outlined above was used by the author in collaboration with Chilean researchers (see Schuller *et al.*, 2007), to assess the effects of introducing a NT management system to replace the conventional tillage practices on rates of soil loss from a field used for cereal production located on a farm in the Coastal Mountains of south-central Chile (38º37′S 73º04′W). The study area is characterized by a mean annual precipitation of 1100 mm year^{-1} and a temperate climate. The shift from CT to NT management occurred in May 1986. Samples were collected from an area of approx. 5000 m^2 selected to be representative of the area affected by soil erosion during the period of CT. The main sampling campaign was undertaken in 2003 and it was therefore possible to estimate rates of soil loss from the study area for a 32-year period under CT (1954–1986) and a 16-year period under NT (1986–2003). Results were obtained for 34 sampling points located on five slope transects and the findings of the study are summarised in Table 1.

Table 1 A comparison of mean annual soil redistribution rates documented using ^{137}Cs measurements for the same area of a study field in south-central Chile during periods under CT (1954–1986) and NT (1986–2003) (based on Schuller *et al.*, 2007).

	Conventional tillage (CT)	No-till (NT)
Years	1954–1986	1986–2003
Period	32 years	16 years
Precipitation	~1100 mm year^{-1}	~1100 mm year^{-1}
Eroding zone		
Mean erosion	11±2 t ha^{-1} year^{-1}	13±2 t ha^{-1} year^{-1}
Fraction of total area (%)	100	57
Aggrading zone		
Mean sedimentation	0 t ha^{-1} year^{-1}	14±2 t ha^{-1} year^{-1}
Fraction of total area (%)	0	43
Total area		
Gross erosion	11±2 t ha^{-1} year^{-1}	7.3±2 t ha^{-1} year^{-1}
Net erosion	11±2 t ha^{-1} year^{-1}	1.4±2 t ha^{-1} year^{-1}
Sediment delivery ratio (%)	100	19

The results presented in Table 1 provide evidence of a major reduction in the net soil loss from the study area. This was reduced by nearly an order of magnitude from approx. 11 t ha^{-1} year^{-1} to approx. 1.4 t ha^{-1} year^{-1}. It is, however, important to note that this reduction was primarily a reflection of a major expansion of the area of the field subject to deposition, since erosion rates within the eroding zone showed little change. The marked reduction in the sediment delivery ratio from approx. 100% to approx. 19% has important implications for sediment inputs to local water courses. Analysis of the long-term rainfall records for a local station demonstrated that the changes documented in Table 1 primarily reflected the change in land management rather than changes in the magnitude and intensity of rainfall inputs.

UPSCALING THE USE OF ^{137}Cs MEASUREMENTS

The approach

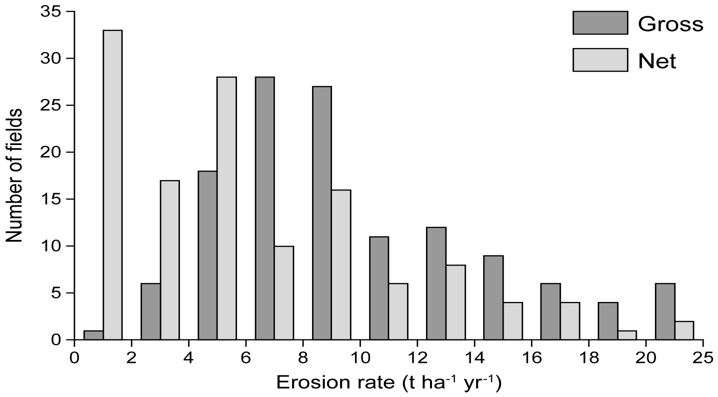
As indicated above, a key feature of most existing studies involving the use of ^{137}Cs measurements to investigate soil and sediment redistribution and sediment budgets has been the emphasis on small areas, frequently individual fields. If fallout radionuclides are to be more widely used as an operational tool to support policy, as distinct from a research tool, there is a need to upscale their application. Analytical requirements, including the relative long count times (e.g. approx. 12 h) and the relative high cost of gamma spectrometers, which inevitably limits the number of detectors available in most laboratories, means that it is not feasible to upscale by simply collecting and analysing a greatly increased number of samples. There is a need to devise novel sampling strategies that permit the use of ^{137}Cs measurements at the reconnaissance scale. Recent work by the author and a co-worker, Dr Yusheng Zhang, has demonstrated the potential for using a limited number of samples collected along a transect to characterize the erosion rates in a field. By selecting fields of similar size and simple topography, but representative of a wide range of conditions known to influence soil erosion rates, including soil texture, slope steepness, effective rainfall and land use, it was possible to commence the production of a national scale database on soil erosion rates on agricultural land (see Walling & Zhang, 2010).

In this study, detailed investigations were undertaken in a number of fields to assess the potential for using a small number of samples collected along a carefully positioned downslope transect to provide a meaningful assessment of the gross and net erosion rates in a given field. The transect data were processed using a conventional mass balance model and the diffusion and migration model (see Walling & He, 1999) for cultivated and non-cultivated fields, respectively, and estimates of the gross and net erosion rates in the field were derived by integrating the resulting estimates of soil redistribution rate along the length of the transect. Comparison of the results provided by the single transect with those provided by much denser grid or transect sampling networks, using the same conversion models, confirmed the validity of the approach and indicated that a transect comprising approx. 10–15 sampling points was capable of providing a reliable estimate of the gross and net erosion rates within individual fields.

A national scale data base

A national sampling campaign was subsequently undertaken to obtain estimates of gross and net erosion rates from 248 fields located in different areas of England and Wales. The data collected are summarized in Fig. 1, which distinguishes the erosion rate estimates obtained for arable and pasture fields. These data have provided a basis for assessing the range of erosion rates occurring on agricultural land in England and Wales. The gross and net erosion rates documented for arable fields ranged between 1.2 and 29.3 t ha^{-1} year^{-1} and 0.0 and 27.3 t ha^{-1} year^{-1}, with median rates of 6.6 and 5.2 t ha^{-1} year^{-1}, respectively. The equivalent ranges for pasture were 0.7 to 13.0 t ha^{-1} year^{-1} and 0.0 to 11.7 t ha^{-1} year^{-1}, with median values of gross and net erosion of 2.6 and 1.8 t ha^{-1} year^{-1}, respectively. The ratio of net to gross erosion, which provides a useful measure of potential sediment delivery to watercourses, was typically >0.6 for arable fields and <0.6 for pasture fields, emphasizing the lower efficiency of delivery from pasture areas. Comparison of the erosion rates obtained from the study with existing erosion hazard assessments, based on soil texture, confirmed the broad consistency of the results. The assembled data set also provided a basis for exploring the

(a) **Arable fields**



(b) **Pasture fields**

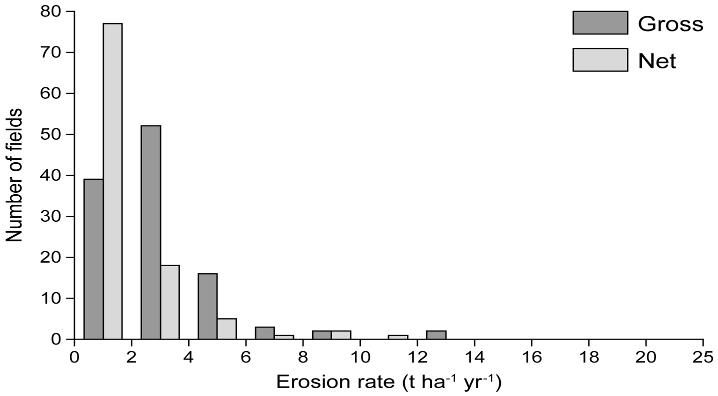


Fig. 1 Frequency distributions of mean annual gross and net erosion rates for the arable and pasture fields sampled in the project.

influence of a range of potential controlling variables on soil erosion rates, using a range of statistical techniques. No very strong relationships existed, but several statistically significant relationships between the erosion rate variables and slope gradient and soil texture were found. The data have also been used to develop a typology for extrapolating information on gross and net erosion rates, based on land use, soil texture and slope steepness, and this has been coupled with a GIS to produce national scale maps of gross and net rates of soil loss from agricultural land in England and Wales, and a preliminary national scale inventory of soil loss for England and Wales.

EXTENDING THE TIMESCALE FOR USING ^{7}Be MEASUREMENTS TO DOCUMENT SOIL REDISTRUBTION BY EROSION

The context

As indicated above, ^{7}Be measurements provide potential to document soil redistribution rates over much shorter periods than is possible with ^{137}Cs or ^{210}Pb$_{ex}$. By virtue of its very short half-life (53 days), it is possible to obtain estimates of the soil redistribution associated with individual events or short periods of heavy rainfall. This makes it possible to investigate erosion or soil redistribution at the event scale or to assess changes in erosion associated with changing land use or management practices. The approach generally employed closely parallels that used with ^{137}Cs and ^{210}Pb$_{ex}$ for longer periods (see Blake *et al.*, 1999; Walling *et al.*, 1999; Schuller *et al.*, 2006; Sepulveda *et al.*, 2008). Samples are collected both from the study area and an adjacent reference site at the end of the event or period under investigation and estimates of soil redistribution are obtained by comparing the inventories measured at individual sampling points with the reference inventory. However, this approach involves two key assumptions or requirements. The first is that the ^{7}Be areal activity density can be assumed to have been essentially homogeneous across the study site, prior to the event or short period of heavy rainfall under investigation. The second is that the relationship between the reduction of the ^{7}Be inventory measured at the time of sampling and the mass of soil eroded or deposited at a sampling point remains constant during the period considered. The first requirement is important, since it ensures that the soil redistribution documented by the ^{7}Be measurements relates only to the event or short period under investigation and does not reflect redistribution of ^{7}Be associated with earlier events. This requirement effectively limits the use of the technique to erosion events occurring either after a long dry period or a period with little or no intense rainfall likely to cause erosion, or shortly after the study area has been tilled. By mixing the existing ^{7}Be into the cultivation layer, tillage will reduce the surface activity below the level of detection. To meet the second requirement, the technique can only be applied to a single event or short period of heavy rainfall. This is because if erosion occurs during two events separated by an appreciable period of time, the effects of radioactive decay will mean that the change in the final measured inventory, relative to the reference inventory, resulting from a given amount of erosion or deposition, will be less for the earlier event than for the later event. As a result, the total amount of erosion or deposition will be under-estimated. Walling *et al.* (2009) have demonstrated that if the period considered extends over about 4 weeks and rainfall events are distributed through this period, the estimates of erosion obtained are likely to underestimate the true values by approx. 40%. As the length of the period increases, the errors will exceed 50%.

Taken together, these two requirements impose important constraints on the potential for using ^{7}Be measurements to document short-term soil redistribution rates. In many areas of the world, the existence of a well-defined dry season preceding a wet season can make it relatively easy to conform with the first requirement, but the ability to document only the soil redistribution associated with the first or first few events after the dry period is likely to represent a major constraint. This situation was, for example, faced by the author and his collaborators, including Professor Paulina Schuller, when investigating soil redistribution occurring after forest harvesting operations in south-central Chile. In this location, there is a season with relatively low rainfall extending from approx. October to April, which is followed by a wet season extending from approx. May to September. The forest harvesting commonly occurs during the dry season and this period of low rainfall will generally make it possible to meet the first requirement for using ^{7}Be measurements to document soil redistribution rates during the subsequent wet season. However, in order to obtain representative information on the soil redistribution occurring after forest harvesting, there is a need to consider a substantial portion of the wet season, extending over two or three months, rather than only the first few events, which could be of relatively low magnitude. This situation prompted an attempt to extend the timescale that can be covered by the approach.

Extending the timescale

The approach developed to permit the use of ^{7}Be measurements over longer timescales is described in detail by Walling *et al.* (2009). In brief, there is a need to extend the sampling programme commonly employed with ^{7}Be and involving collection of samples at the end of the event or study period, to include measurement of the reference inventory and the ^{7}Be depth distribution at the beginning of the study period and, if possible, on several occasions through the study period. In addition a record of rainfall input is required. The periodic measurements of the reference inventory, when combined with the record of rainfall for the intervening periods, make it possible to estimate the mean ^{7}Be activity in rainfall from the magnitude of the change in the reference inventory, whilst taking account of the effects of radioactive decay in reducing the accumulating inventory. Information on changes in the ^{7}Be depth distribution can also be used to take account of changes in its form, as reflected by the relaxation depth, during the study period. The rainfall record can also be used to distribute erosion during the study period, using a measure of rainfall erosivity, such as that incorporated into the Revised Universal Soil Loss Equation (RUSLE). By using a mass balance model with a daily timestep, to take account of fallout inputs and radioactive decay, and distributing the erosion or deposition through the study period in proportion to the rainfall erosivity, it is possible to estimate the soil redistribution rate required to account for the ^{7}Be inventory measured at a sampling point at the end of the study period.

Application in a Chilean case study

The application reported below, which was undertaken in collaboration with researchers from the Universidad Austral de Chile and is described in more detail by Walling *et al.* (2009), focused on a study site located at El Monumento within the Forest Research Centre of the Universidad Austral de Chile (39°44′25″S, 73°09′58″W), near the city of Valdivia, in south-central Chile. The study area experiences a temperate climate with a mean annual rainfall of approx. 2300 mm year^{-1} (Huber, 2004). Most rain falls between late autumn and early spring, when high precipitation intensities can occur. The study aimed to document the impact of clearcutting of a *Pinus radiata* plantation and exposure of the cleared area to winter rainfall on soil loss, and to assess the potential for using trash barriers constructed from the woody trash remaining after harvesting. Forest harvesting at the study site occurred during December 2005. The soil remained covered by forest residues until woody trash barriers were constructed in early March 2006. These trash barriers were constructed along the contour with a spacing of 30 m and 15 m. After construction of the trash barriers, a number of plots were established in order to document soil loss during the ensuing winter and to assess the effectiveness of the trash barriers in reducing net erosion. Here attention focuses on a plot 7.5 m wide and 30 m long and oriented parallel to the dominant flow direction, with a slope of 30%, which was bounded by trash barriers along its upper and lower boundaries.

To document the post-harvest erosion and soil redistribution occurring on the plot during the period of approx. 3 months extending from late March 2006 until late June 2006 (see Fig. 2(a)), the study plot was sampled for ^{7}Be measurement on 21 June. Shallow soil cores (4 cm deep) were collected from 10 equally spaced locations along two downslope transects within the plot, using a 10.6-cm diameter cylindrical plastic core tube. Three shallow cores were collected from each sampling point and these were subsequently bulked to be assayed as a single sample. An adjacent flat area located within the harvested area that showed no evidence of erosion or deposition was selected as a reference site. Two sets of eight cores were collected using the same plastic core tubes, in order to determine the reference inventory and to characterize the relaxation mass depth of the ^{7}Be depth distributions. The cores from the reference site were collected at the beginning of the study period on 31 March 2006, and at approximately monthly intervals (28 April, 2 June), as well as at the end of the study period (21 June). In order to define the depth distribution of ^{7}Be, each set of eight cores was sectioned into 2-mm increments in the laboratory and the slices representing specific depth increments were bulked for assay as a single composite sample.

Figure 2(b) presents estimates of the daily ^{7}Be fallout input to the plot, based on the measured changes in the reference inventory over the study period, and the synthesized record of the ^{7}Be inventory at the reference site over the same period. Figure 2(c) shows daily values of the erosion index, based on the $E \times I_{30}$ erosivity index (see Renard *et al.*, 1997), used to distribute the erosion and deposition throughout the study period. The estimates of soil redistribution obtained for the sampling points on the two transects over the period 31 March–21 June 2006, based on the cores collected from those points on 21 June 2006 are presented in Table 2. These results confirm that significant soil loss occurs from the bare soil of the clear-felled areas during the ensuing winter. On this plot, the trash barriers with a 30-m spacing appear to have had little effect in reducing net soil loss, since the sediment delivery ratio for the plot remained high (>80%). However, results from other plots demonstrated that a trash barrier spacing of 15 m was considerably more effective in reducing the sediment delivery ratio and the net soil loss.

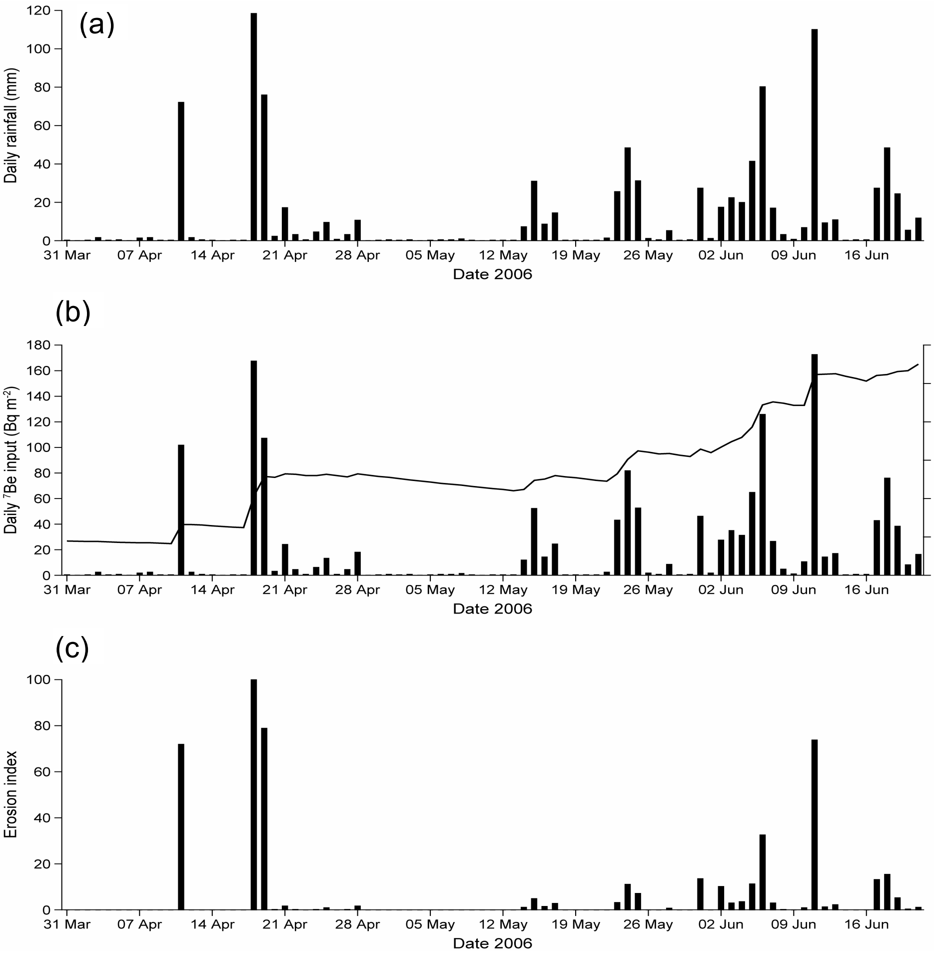


Fig. 2 The rainfall record for the period covered by the ^{7}Be measurements in the study undertaken at the El Monumento site (a), the reconstructed record of daily ^{7}Be fallout for the study period (b) and (c) the temporal distribution of erosion during the study period, as represented by the daily relative erosivity index based on estimates of $E \times I_{30}$. (Based on Walling *et al.*, 2009).

Table 2 Estimates of soil redistribution rates for the period 31 March–21 June 2006 obtained from the ^{7}Be measurements undertaken on the 20 composite soil cores collected from a 30-m plot within an area of recently harvested forest at El Monumento, near Valdivia in south-central Chile. (Based on Walling *et al.*, 2009.)

Transect A			Transect B		
Sampling point	^{7}Be inventory (Bq m^{-2})	Soil redistribution rate (kg m^{-2})	Sampling point	^{7}Be inventory (Bq m^{-2})	Soil redistribution rate (kg m^{-2})
1	701± 54	–1.6	1	955 ± 76	–0.5
2	1003 ± 66	–0.3	2	1061± 81	–0.2
3	748 ± 53	–1.3	3	619 ± 59	–2.1
4	874 ± 51	–0.8	4	1159 ± 83	0.3
5	949 ± 63	–0.5	5	1198 ± 82	0.4
6	746 ± 55	–1.3	6	1132 ± 81	0.2
7	685 ± 55	–1.7	7	1200 ± 125	0.5
8	834 ± 61	–0.9	8	991 ± 80	0.3
9	1179 ± 75	0.3	9	1055 ± 80	–0.1
10	1046 ± 81	–0.2	10	696 ± 101	–1.7
Total Plot					
Gross erosion rate (kg m^{-2})		–0.6			
Net erosion rate (kg m^{-2})		–0.5			
Sediment delivery ratio (%)		82			

CONJUNCTIVE USE OF ^{7}Be AND ^{137}Cs MEASUREMENTS

The context and basis

As indicated above, the use of two fallout radionuclides can frequently provide additional information on the erosional history of a site. The conjunctive use of ^{137}Cs and ^{210}Pb$_{ex}$ can provide information relating to the past 100 years. The combined use of ^{7}Be and ^{137}Cs, as reported by Walling *et al.* (1999) and Sepulveda *et al.* (2008), arguably provides more valuable information, by permitting comparison of current short-term erosion rates, documented with ^{7}Be, with longer-term erosion rates over the past approx. 50 years, documented using ^{137}Cs. This scenario clearly offers considerable potential for assessing the relative importance of extreme events or the effects of changing land use. The scope for using ^{7}Be measurements to document recent erosion may be limited by the need to identify a short period of erosion that fulfils the requirements for applying the approach, but the possibility of extending the timescale for using ^{7}Be measurements outlined above greatly increases the potential for using these two radionuclides in combination. In many situations, soil sampling for both radionuclides can be undertaken contemporaneously. An example of the conjunctive use of ^{137}Cs and ^{7}Be to assess the effects of changing land use on erosion rates is provided below.

Assessing the impact of the expansion of maize cultivation on soil erosion rates

The recent expansion of the cultivation of fodder maize in many areas of the UK, including southwest England, has raised important concerns over increased soil erosion rates and sediment inputs to watercourses. These problems stem from the harvesting practices involved. Harvesting takes place relatively late in the year, usually in October, and the use of heavy equipment can cause soil compaction and the creation of wheelings, which cause increased surface runoff, erosion and sediment mobilisation. Frequently, the fields are left in a bare and compacted state until the following spring, when they are ploughed and tilled for new crops.

In order to provide a reliable assessment of the increased rates of soil loss caused by maize cultivation there is a need to compare recent erosion rates in fields under maize with the longer-term erosion rates in those fields, associated with more traditional land use. This can be achieved by the conjunctive use of ^{7}Be and ^{137}Cs measurements. The former can provide an estimate of the soil redistribution associated with winter rainfall during the post-harvest period, whereas the latter can provide an estimate of the longer-term soil redistribution rate in the same field over a period of approx. 50 years. The latter estimate will incorporate some recent years with increased erosion rates associated with maize cultivation, and thus a comparison of the two estimates of soil redistribution rates will effectively provide a minimum estimate of the increase in erosion rates associated with maize cultivation.

The occurrence of heavy rainfall in the post-harvest period in the autumn and early winter will frequently provide a suitable situation for the use of ^{7}Be measurements, to estimate the soil redistribution involved. The autumn or winter rain is likely to follow an extended period of limited rainfall, as required for the use of ^{7}Be measurements to estimate erosion rates. Depending on the duration of the period of heavy rainfall studied, either the "standard" (e.g. Blake *et al.*, 1999; Schuller *et al.*, 2006) or the "extended timescale" (see above) ^{7}Be approaches could be used. Sampling for ^{7}Be can also be combined with the collection of deeper soil cores for ^{137}Cs assay and the resulting data could be used to estimate longer-term soil redistribution rates in the same field. It may, however, be necessary to apply different criteria in selecting reference sites for the two sets of measurements, since the ^{137}Cs reference site should have experienced no gain or loss of soil over the past 50 years, whereas, for ^{7}Be, the period of interest relates involves only the immediate past and thus the period of rainfall under investigation. Furthermore, bare areas should be used as reference sites for ^{7}Be, since the existence of a vegetation cover can introduce problems in terms of both radionuclide trapping by the vegetation cover and an increase in the spatial variability of fallout receipt due to rainfall interception by the canopy.

The approach described above has been successfully used by the author and a co-worker, Mokhtar Jaafar, to assess the impact of recent maize cultivation on erosion rates in six representative maize fields in East Devon and West Somerset. These fields were sampled in mid-January 2005 after a period of heavy rainfall extending over several weeks from early December 2004 until early January 2005. The total rainfall during this period within the study area ranged from approx. 115 mm to 145 mm and field observations recorded extensive erosion on the bare post-harvest maize fields. The six fields ranged in size from 3.2 to 11.0 ha, and samples for both ^{7}Be and ^{137}Cs analysis were collected from two downslope transects in each field. Samples were collected from approx. 25 sampling points in each field. The estimates of erosion associated with the period of heavy rainfall between December 2004 and January 2005 and of longer-term mean annual erosion rates for the six fields are presented in Table 3.

Table 3 A comparison of the estimates of short- and longer-term gross and net erosion rates and the associated sediment delivery ratio provided by ^{7}Be and ^{137}Cs measurements for six study fields in southwest England.

Field	Gross erosion			Net erosion			Sediment delivery ratio (%)		
	^{7}Be ($t\ ha^{-1}$)	^{137}Cs ($t\ ha^{-1}\ year^{-1}$)	Increase ×	^{7}Be ($t\ ha^{-1}$)	^{137}Cs ($t\ ha^{-1}\ year^{-1}$)	Increase ×	^{7}Be (%)	^{137}Cs (%)	Increase ×
1	31.3	10.4	3	24.2	3.4	7.1	77	33	2.3
2	46.7	7.2	6.5	42.3	6.4	6.6	89	89	0
3	41.1	6.2	6.6	38.7	4.1	9.4	95	66	1.4
4	21.4	9.1	2.3	19.7	3.6	5.5	89	40	2.2
5	31.5	7.3	4.3	18.1	1.6	11.3	55	22	2.5
6	34.6	8.9	3.9	32.6	2.5	13	94	28	3.3
Mean	34.4	8.2	4.2	29.3	3.6	8.1	83	46	1.8

For all fields, the gross and net erosion associated with the short period of heavy rainfall in December 2004 and early January 2005 greatly exceeds the longer-term mean annual erosion rates, thereby emphasizing the major impact of maize cultivation in increasing erosion rates from bare post-harvest fields. It is important to recognise that the estimates based on the ^{7}Be measurements relate only to a short period in late 2004 and early 2005 and that the annual erosion rate is likely to be significantly higher. Equally, since the "standard" rather than the "extended timescale" approach was used for the ^{7}Be measurements, it is likely that the estimates of erosion obtained for the six field may underestimate the true values. Furthermore, as indicated above, the estimates of the longer-term mean annual erosion rate provided by the ^{137}Cs measurements will incorporate several recent years with increased erosion, and may thus overestimate the longer-term erosion rate associated with the more traditional land use. In this context, the estimates of the magnitude of the increase in gross and net erosion and the sediment delivery ratio can be seen as minimum estimates of the change involved. The mean values for the six fields indicate that the gross erosion documented for the maize fields during the study period were approx. 4 times greater than the longer-term mean annual erosion rates, whilst the net erosion was approx. 8 times greater. The greater increase for net erosion reflects the increased sediment delivery ratios for the fields in late 2005 and early 2005, which were almost double the longer-term values. These greatly increased rates of net soil loss and the increased sediment delivery efficiency clearly have important implications for increased sediment transfer to local water courses.

USE OF THE CHERNOBYL SIGNAL TO PROVIDE IMPROVED ^{137}Cs CHRONOLOGIES FOR FLOOD PLAIN AND LAKE DEPOSITS

Current concern for environmental degradation, and the introduction of improved environmental management to counter such trends, has generated an increasing need for assessment of the changing ecological status of freshwater systems. Such assessment could include reconstruction of past conditions, which might be indicative of "good ecological status", documentation of the progressive degradation of aquatic ecosystems during the 20th century and, provision of evidence of improvements in ecosystem health. The frequent lack of direct records of such changes has directed attention to other potential sources of information. The sediment deposits found in lakes and associated with overbank deposition on river flood plains can provide important archives of changes in the pollution status of aquatic systems. Sediment cores from lakes and flood plains can provide valuable information on changes in sediment-associated nutrient and pollutant transport and downcore changes in sediment geochemistry have been used to reconstruct changing sediment sources within a river basin (e.g. Walling *et al.*, 2003; Pittam *et al.*, 2009; Collins *et al.*, 2010). Provision of such evidence and information is, however, highly dependent on the establishment of a reliable chronology for the sediment column used as the archive. $^{210}Pb_{ex}$ has been widely used to date lake sediments and similar approaches have been used for flood plain sediments (see He & Walling, 1996). However, in some situations, chronologies based on $^{210}Pb_{ex}$ measurements will involve appreciable uncertainty by virtue of the indirect nature of the dating procedure. This is based on an assessment of the downcore reduction in $^{210}Pb_{ex}$ activity, coupled with various assumptions regarding the original source of the $^{210}Pb_{ex}$ and the activities and fluxes involved. ^{137}Cs provides a valuable alternative chronometer, since the peak of ^{137}Cs fallout in 1963 is commonly directly evidenced by a peak in the downcore record of ^{137}Cs activity in a sediment core. However, this peak provides only a single time marker in the sediment column and development of a detailed chronology may be hampered by the potential for changing sedimentation rates, particularly in river basins that have been heavily impacted by human activity in recent years.

In many parts of Europe that were affected by fallout from the Chernobyl disaster in 1986, that event can potentially provide a second time marker. It is now more than 20 years since the Chernobyl disaster and the availability of time markers for 1963 and 1986 in a sediment core can provide a valuable basis for assessing changes in sediment-associated pollutant transport and ecosystem health over the past approx. 50 years. Figure 3 provides an example of a sediment core

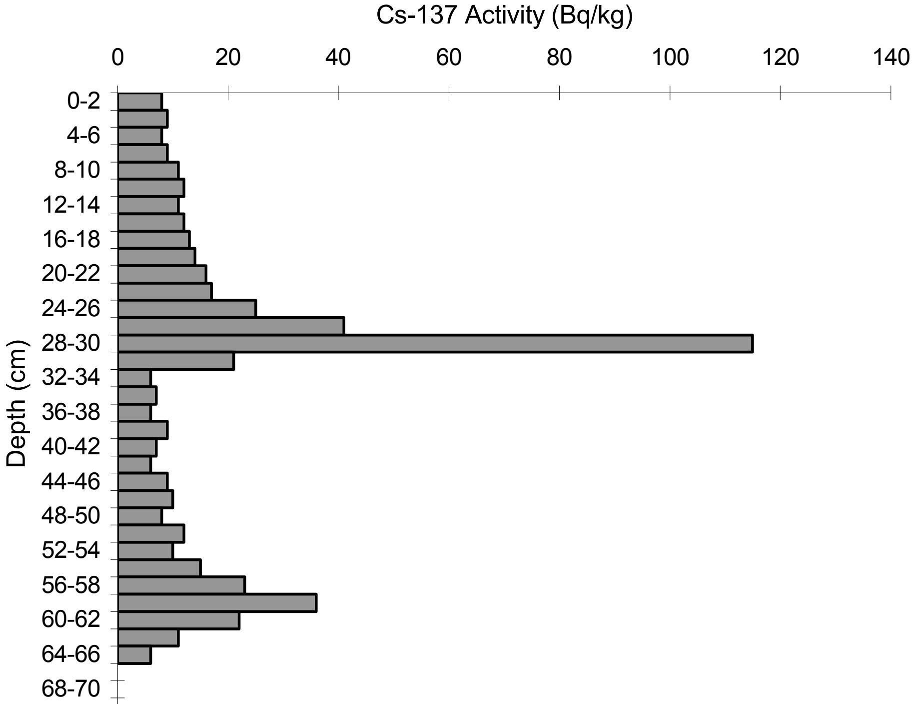


Fig. 3 Time markers provided by the 1963 and 1986 ^{137}Cs peaks in a sediment core collected from the flood plain of the River Severn near Welshpool, UK.

collected from the flood plain of the River Severn near Welshpool, UK, where it has been possible to identify clear signals related to both the 1963 bomb fallout peak and the Chernobyl fallout in 1986. The ^{137}Cs inventory for the core is considerably greater than the local reference inventory and the two radiocaesium peaks reflect both direct fallout to the flood plain surface and mobilisation of sediment containing ^{137}Cs from the surface of the upstream catchment, which was subsequently deposited on the flood plain during overbank flood events. At this site, the rate of overbank sediment accretion appears to have changed little between 1963–1986 and 1986–2008 and, since the site is inundated on several occasions each year, it is reasonable to assume that the annual sedimentation rate has remained relatively constant. In this situation, there is potential to use the sediment core to reconstruct a detailed record of changes in the nutrient and pollutant content of the sediment transported by the river over the past approx. 50 years.

PERSPECTIVE

This overview has provided five examples of recent advances in the use of fallout radionuclides in erosion and sediment delivery investigations. These advances build on earlier work and further expand the potential for using fallout radionuclides as sediment tracers. It is important that such development work should continue, in order to explore and exploit further applications and opportunities. The initiatives taken by the International Atomic Energy Agency to further such work are to be welcomed. As sediment management in catchments and river basins becomes increasingly important, there is a need to ensure that these important new techniques become more widely used to support policy and practice and to help address the increasingly complex questions which will undoubtedly face catchment managers in the future.

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