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The use of the environmental isotope caesium-137 as a tracer for soil erosion study

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Abstract: The fallout isotope caesium-137 (^{137}Cs), a product of thermonuclear weapon tests, has been distributed globally and become part of the world ecosystem. For the last 25 years of research, the fallout radionuclide ^{137}Cs has been used as an indicator of soil erosion and sediment deposition status. The fallout radionuclide ^{137}Cs reached the earth surface primarily in association with precipitation. On reaching the earth surface, ^{137}Cs has become firmly adsorbed to surface soils particularly clay minerals. Fallout from atmospheric weapons testing during the 1950s to 1970s has labelled soil materials, so the sites with no net soil loss should have ^{137}Cs inventories that reflect the amount of ^{137}Cs fallout. The level of ^{137}Cs at an undisturbed site should provide a reference value for assessing the degree of erosion and deposition within the area, where sites with less than the reference value can be considered eroded, and sites with more than the reference value can be regarded as depositional. This paper will highlight the advantages and detail information concerning the ^{137}Cs technique.

INTRODUCTION

Deforestation and poor farming practices are responsible for about 30 per cent of soil degradation worldwide. These human activities leave soils exposed to accelerated water and wind erosion. Soil erosion and the subsequent deposition of eroded soil particles affect the productivity of soil in significant ways. It may cause chemical deterioration through loss of nutrients or the accumulation of salts or acids, and physical deterioration from compaction by heavy machinery or water logging (Elliott *et al.*, 1990). To solve these problems, better and reliable information is needed on sources, locations, patterns and rate of erosion and deposition of eroded materials for different agroecosystems and land uses. This information is essential for assessing the magnitude of the erosion problems as well as for obtaining a better understanding of the environmental controls involved, for developing improved prediction procedures and for formulating improved land management strategies (Walling and Quine, 1995).

Many methods, including models for predictions, have been developed and used to obtain qualitative and quantitative data on patterns and rates of erosion and sediment accumulation. However, existing techniques for monitoring soil erosion have a number of limitations (Loughran, 1989), including high cost, lack of representativeness, the need for long-term observations, and the spatially-lumped nature of the resultant soil loss data, which frequently provide little or no indication of the spatial patterns involved. Because of these limitations, the measurement of several fallout radionuclides, in particular ^{137}Cs, have attracted increasing interest as a means of documenting medium-term (i.e. ca 30 years) rates of soil loss and the spatial patterns involved on the basis of a single visit. The potential of using ^{137}Cs technique in soil erosion and sediment budget investigations was first recognised in the 1970s in the USA (Ritchie *et al.*, 1974) and has attracted increasing attention in recent years in a number of cases (Walling and Quine, 1990, 1992, 1995), The application of ^{137}Cs technique has shown that in many cases, it not only confirms the results obtained by conventional methods but as alternative, this technique provides more information and answers to some soil erosion and sediment deposition status.

THE ^{137}CS TECHNIQUE

The basis

The environmental isotope ^{137}Cs is an artificial radionuclide with a half-life of 30 years, which does not occur naturally but is a product of fission reactions, has been released in the environment during thermonuclear weapons testing. The ^{137}Cs derived from thermonuclear weapon testing was transported into the stratosphere, distributed globally, subsequently deposited as fallout, usually in association with precipitation (Walling and Quine, 1993) and become part of the world ecosystem. Figure 1 illustrates the typical annual pattern of bomb derived ^{137}Cs fallout inputs for the Northern and Southern Hemisphere.

Its value as a sediment tracer lies in its rapid and strong adsorption by soil particles, particularly the clay minerals (Tamura, 1964; Bachhuber *et al.*, 1982; Livens and Baxter, 1988), so that in most agricultural environments its subsequent redistribution is a direct reflection of the erosion, transportation and deposition of soil particles occurring during the period extending from the main phase of atmospheric deposition (late 1950s and early 1960s) to the time of sampling.

Assessment of ^{137}Cs redistribution is commonly based on comparison of the measured sample inventories (total activity per unit area) at individual sampling points, with an equivalent estimate of the local reference inventory representing the cumulative atmospheric fallout at the study site. Where sample inventories are lower than the local reference inventory, loss of caesium labelled soil and therefore erosion may be inferred. Similarly, sample inventories in excess of the reference level are indicative of the addition of the caesium labelled soil by deposition. The magnitude and direction of measured deviations from the local reference level provide a qualitative assessment of sediment redistribution.

To derive quantitative estimates of the rates of soil erosion and aggradation from ^{137}Cs measurement, it is necessary to establish a relationship between the magnitude of the deviation from the reference inventory and the extent of soil loss or gain (Walling and Quine, 1991). Because empirical calibration data are rarely available, many workers have favoured the use of theoretical relationships or models to provide the necessary calibration function. Such models can be used to simulate the effect of a range of long term erosion and aggradation rates upon the ^{137}Cs inventory of soil profiles, and the resultant data can be used to derive the calibration relationship (Walling and Quine, 1991).

Establishment of a Reference Inventory

The basic premise in the use of ^{137}Cs in soil erosion investigations is that the point inventories of ^{137}Cs at study site can be directly compared with the reference inventory for a local, undisturbed, stable sites which reflect the total cumulative input flux of ^{137}Cs. Use of reference inventory values that are inaccurate will result in biased and unreliable estimates of soil erosion and sediment deposition.

It is, therefore, essential to establish the reference inventory with great care. As relevant fallout data are rarely available, it is usual to identify the total input flux by measuring the ^{137}Cs inventory in soil samples collected from sites which are known to have suffered no erosion or disturbance during the period since the onset of ^{137}Cs deposition. These sites are assumed to have received a full complement of atmospheric fallout and to have lost no ^{137}Cs by erosion or leaching but the only loss of ^{137}Cs will be by radioactive decay.

Sampling strategy

It is desirable to collect samples from a number of different reference locations so that unforeseen problems may be identified by comparing results. This is particularly important if the only available sites clearly do not fulfill the criteria of ideal reference sites. Ideal reference sites have the characteristic as that proximity to the study site, same altitude as the study site, same soil series as the study site, no disturbance since 1953, no soil erosion or deposition since 1953, minimal slope angle, full vegetation cover all year and grass or similar vegetation. A minimum of cat 10 whole core samples should be collected from each reference sites, and at least one depth incremental sample sequence. The information gained regarding the depth distribution of ^{137}Cs may allow identification of sites disturbance.

Figure 2 shows two typical ^{137}Cs depth distributions from undisturbed reference locations (a and b), and two depth distributions from sites which were initially though to be appropriate as reference locations (c and d) but on the basis of the profile evidence can be seen to have been disturbed. In the case of profile c there is clear evidence in the uniform depth distribution of ^{137}Cs that the site has been cultivated in the past. In profile d the presence of peak ^{137}Cs at the depth of 5 cm below soil of low ^{137}Cs content suggests that the ground surface has been buried, during the last 30 years, by sediment of unknown ^{137}Cs content. Use of reference inventories established at either site c or d would lead to erroneous identification of ^{137}Cs loss and gain.

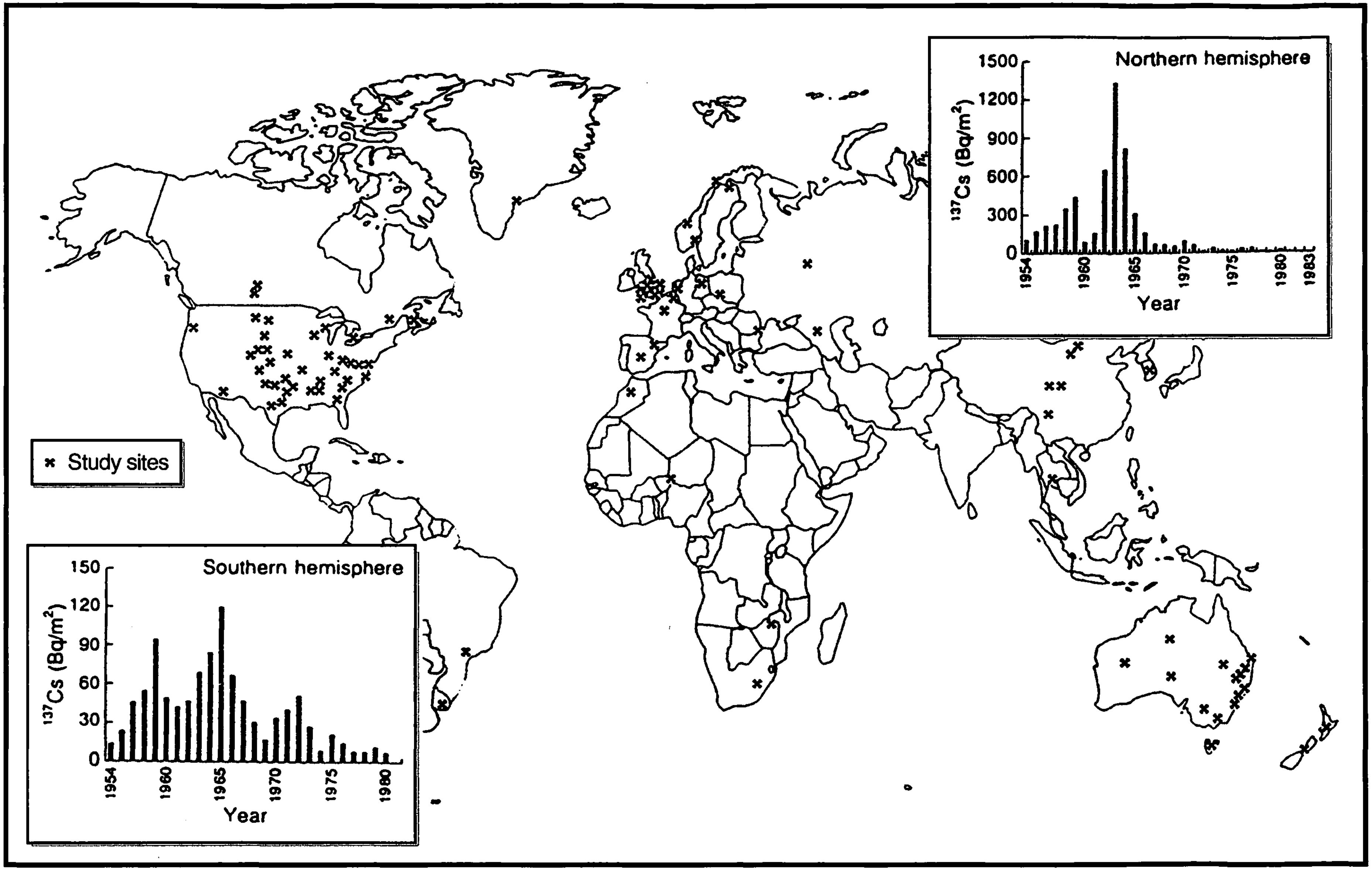

Figure 1. Locations where ^{137}Cs has been used successfully in soil erosion and related studies and typical fallout records for the Northern (New York, USA/Milford Haven, UK) and Southern (Adelaide/Brisbane, Australia) hemispheres.

Sampling study site

The objective of sampling at the study site is quite different from that at the reference site. At the reference site the aim is to identify a single value, the reference inventory. In contrast, at the study site the aim is to identify the current spatial distribution of ^{137}Cs resulting from soil redistribution over the period since the initiation of fallout.

Sampling strategy

In most cases there are two sampling frameworks are commonly used, namely the individual slope transect and the grid.

Individual slope transect

Individual slope transect is appropriate when resources are limited and the sampled fields are characterised by simple topography (Fig. 3). The transects are generally best aligned along the axis of greatest slope, and consist of a sequence of samples, from the upslope to the downslope boundary. The number of samples along the transect will be defined, to a large extent, by the downslope length of the studied field. However, even on the shortest fields, a minimum of Free samples will be required, because it is important to establish the ^{137}Cs inventories close to the upslope and downslope boundaries. The upslope boundary

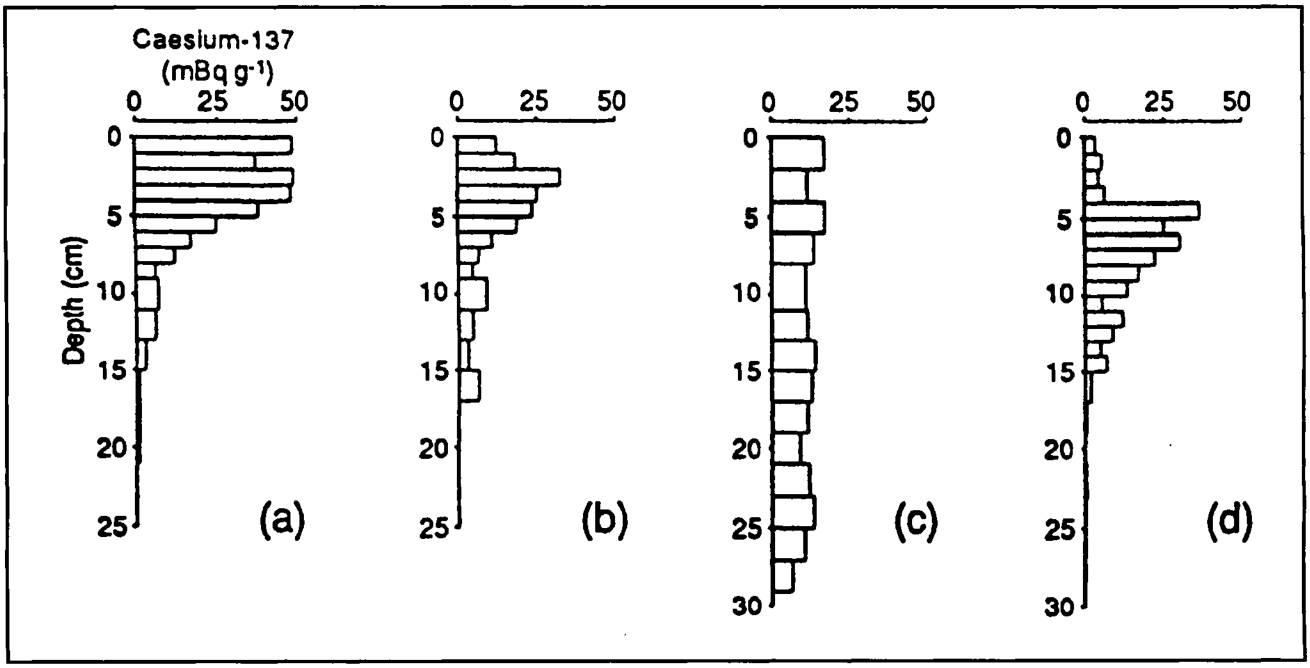

Figure 2. Depth incremental profiles from sites which appeared suitable for the collection of reference samples; (a) and (b) from undisturbed sites; (c) from a previously cultivated site; (d) from a disturbed site.

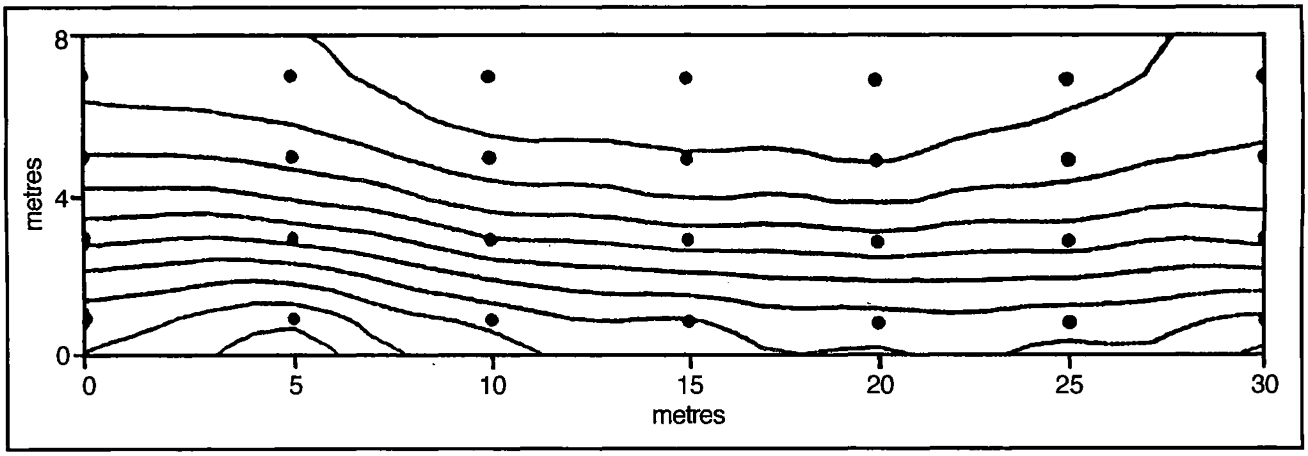

Figure 3. Simple topography.

will often be the area subject to the greatest loss of ^{137}Cs due to tillage displacement, and sediment deposition will be concentrated at the downslope boundary.

Grid frameworks

At study sites where the topography is more complex (Fig. 4), it will not be possible to define effectively the spatial distribution of ^{137}Cs, and therefore the pattern of soil redistribution, on the basis of individual transects. In such cases, it will be necessary to collect samples on a grid framework consisting of numerous transects across the study field.

When the only data required are ^{137}Cs inventories, bulk samples are collected which contain a whole soil profile to a sufficient depth to include all ^{137}Cs present. In order to ensure that this has been achieved, the bottom 2 cm of each profile may be separated and analysed to demonstrate that it contain no ^{137}Cs. When information is required concerning the depth distribution of ^{137}Cs activity, incremental samples are collected, commonly at 1 or 2 cm intervals. In this case analysis is initiated with the uppermost sample, and is continued until samples analysed are found to contain no ^{137}Cs activity.

The ^{137}Cs inventory of the sample S ($mBqcm^{-2}$) is calculated from the following equation:

$$S = C.M.A^{-1}$$

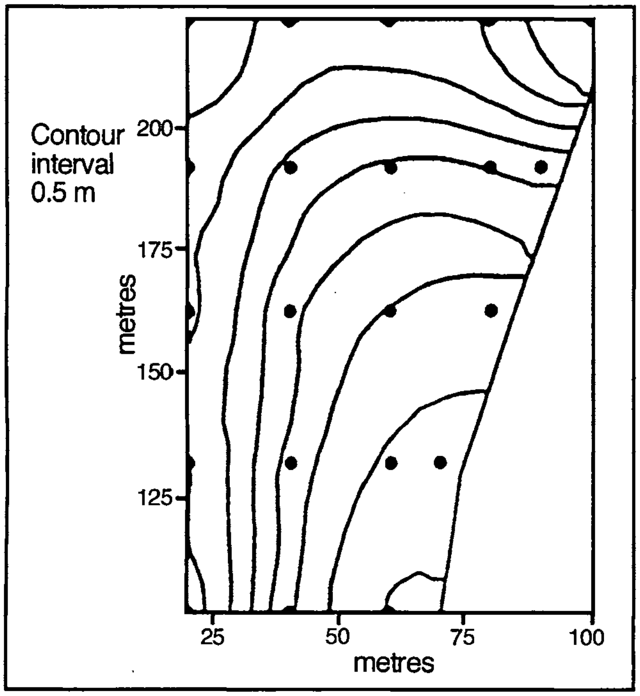

Figure 4. Complex topography.

where C is the ^{137}Cs concentration or activity of the sample < 2 mm (Bqg^{-1}), M is the sample mass (g) and A is the area of the sampling frame, core or auger (cm^2). Error associated with counting is usually expressed as 2σ or at the 95% confidence level.

An example

An example of the potential for ^{137}Cs measurements to assemble detailed information on the pattern of soil redistribution within a 3.8 ha agricultural field at Rufford Forest Farm, Nottinghamshire, United Kingdom reported by Walling and Quine (1991).

This area, which is underlain by brown sand soils of Cuckney 1 association, is primarily used for arable cultivation. Sugar beet is widely gown and soil erosion has frequently been observed in the area (Evans and Cook, 1986), A 20 m x 20 m grid was used as a basis for collecting soil cores from the field and a total of 117 cores were obtained using motorised percussion corer (38 cm^2) inserted to a depth of 60 cm. The reference cores were obtained from an area of uneroded, undisturbed grassland located 1.7 km from the study site.

After collections all the cores were air dried and lightly ground and the ^{137}Cs content of the material passing through a 2 mm sieve was determined by gamma spectrometry using an HpGe coaxial detector. The value of 320 $mBqcm^{-2}$ was obtained for the local reference inventory. Deviations of the inventories associated with the individual sampling points within the field, from the reference value, were subsequently established, and estimates of the medium term rates of erosion and deposition occurring within the field over the past 35 years were derived using a calibration model. The resultant pattern of soil redistribution documented for the field, which is presented in Figure 5, reflects the action of a range of erosion processes, including both water erosion and the effects of soil tillage.

In addition to providing an assessment of the spatial pattern of soil redistribution within the study field, the individual point estimates of the erosion and deposition rates based on the ^{137}Cs measurements can be spatially integrated to produce a range of measures of the overall status of erosion and deposition in the field (Table 1). The values of both the gross erosion rate and the mean erosion rate for the eroding sites permit clear assessment of the severity and potential off-site impact of erosion within the area under investigation.

Table 1. Spatially integrated estimates of soil redistribution in the field at Rufford Forest Farm, as illustrated in Figure 5.

Gross erosion rate ($t.ha^{-1}.a^{-1}$)	12.2
Eroding zone	
Mean erosion rate ($t.ha^{-1}.a^{-1}$)	13.8
% of total area	89
% of area with erosion rates	
> 2 $t.ha^{-1}.a^{-1}$	81
> 4 $t.ha^{-1}.a^{-1}$	72
Aggrading zone	
Mean aggradation rate ($t.ha^{-1}.a^{-1}$)	16.1
% of total area	11
Net erosion rate ($t.ha^{-1}.a^{-1}$)	10.5
Sediment delivery ratio (%)	86

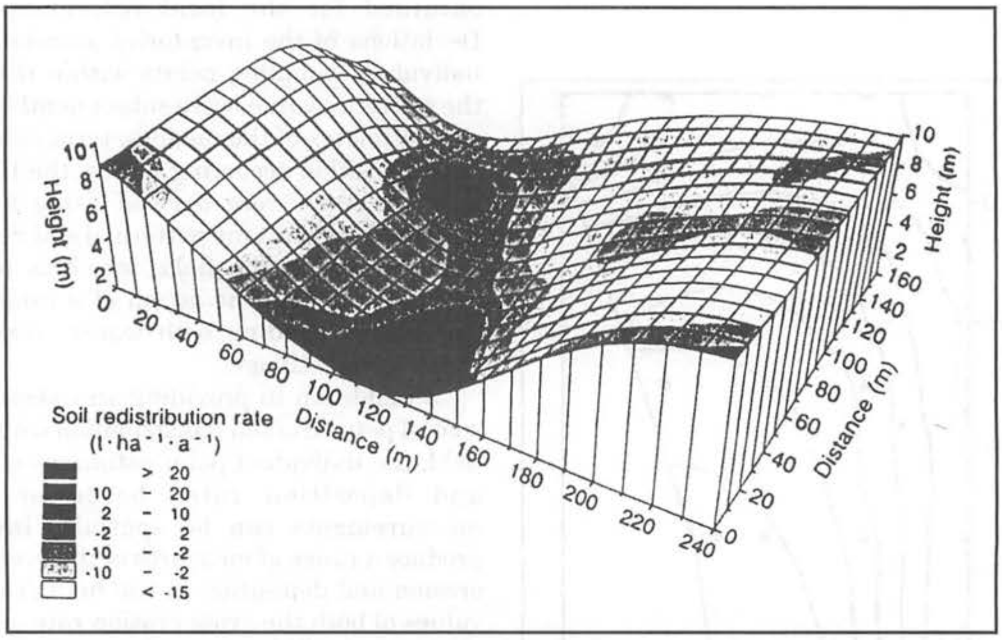

Figure 5. Medium term (35 year) erosion and deposition rates within a field at Rufford Forest Farm, Nottinghamshire, UK, estimated using ^{137}Cs measurements.

CONCLUSION

The value of the ^{137}Cs technique may be seen as follow:

Conceptual benefits

1. The technique permits retrospective assessment of medium-term erosion rates.
2. The soil redistribution rates estimated represent an average for the last 30-35 years, and are therefore less influenced by extreme events.
3. The rates estimated represent the sum of all erosive processes.
4. Both rates and patterns of soil redistribution may be quantitatively assessed.
5. A range of erosion rate estimates may be obtained, including mean rates of erosion and deposition and net rates of soil export from the field.
6. The spatial resolution of the data obtained is defined by the sampling strategy.

Practical benefits

1. The application of the technique requires only one field visit, and the results can be provided within a relatively short time.
2. The whole field may be studied with minimal disturbance to the land-user.
3. Erosion rate data may be obtained at a range of spatial scales from the detailed-field investigation to a reconnaissance-level study.
4. When combined with extrapolation procedures and other methods for maximising apatial coverage the technique offers a cost-effective means of assembling quantitative catchment-scale data.

The technique, therefore, has unique potential for meeting the data requirements of agencies involved in on-site and off-site erosion assessment, evaluation of soil conservation methods and development of land management strategies.

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