Variability in Stream Erosion and Sediment Transport (Proceedings of the Canberra Symposium, December 1994). IAHS Publ. no. 224, 1994.

Quantifying soil erosion and sediment transport in drainage basins; some observations on the use of ^{137}Cs

I. D. L. FOSTER, H. DALGLEISH, J. A. DEARING & E. D. JONES

Centre For Environmental Research and Consultancy, Coventry University, Priory St, Coventry CV1 5FB, UK

Abstract This paper presents the results of studies undertaken in Midland England which permit an evaluation of the use of ^{137}Cs in order first, to quantify patterns and rates of soil redistribution on hillslopes and, secondly, to interpret the erosional history of drainage basins from ^{137}Cs profiles in reservoir sediments.

INTRODUCTION

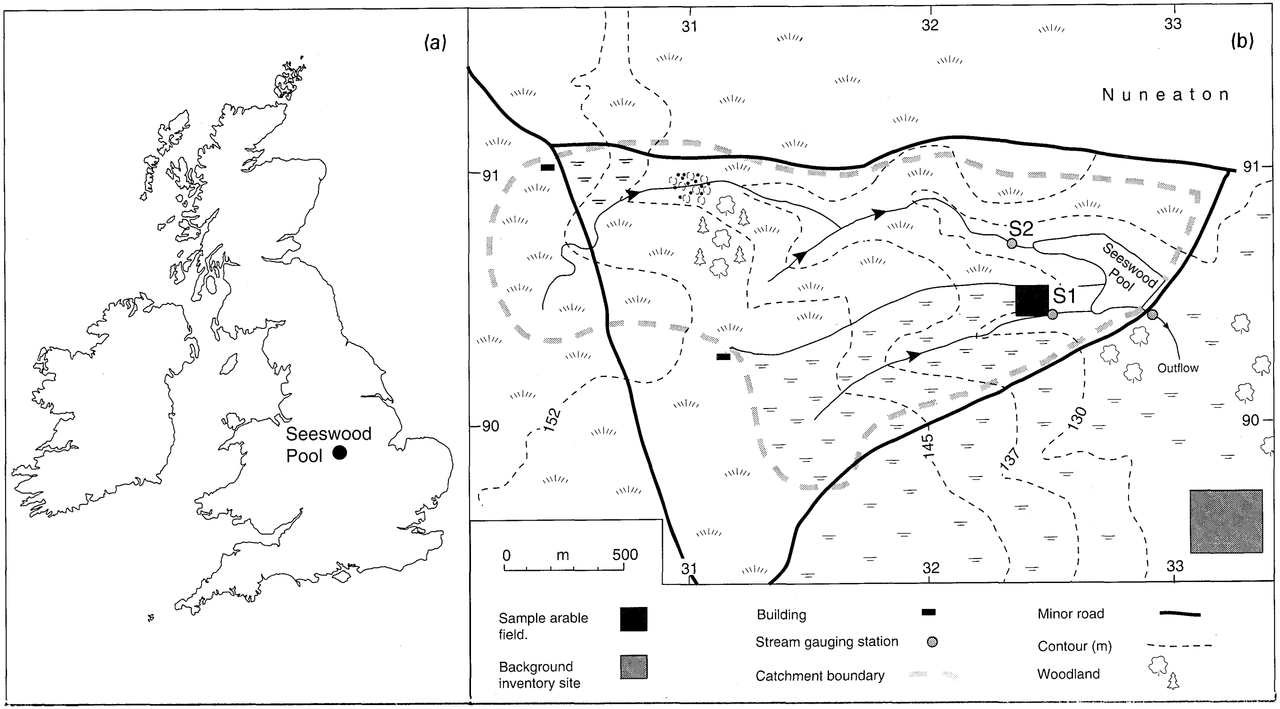
^{137}Cs has been used in a range of geomorphological, hydrological and limnological studies for several purposes, including the measurement of soil redistribution and flood plain sediment accumulation (Loughran *et al.*, 1987; Walling & Bradley, 1990), the fingerprinting of sediment sources (e.g. Peart & Walling, 1988) and in the provision of a chronology for lake and reservoir sediments (e.g. Foster *et al.*, 1985). Recent attention has focused upon the validity of comparing background ^{137}Cs inventories with inventories at eroding and depositing sites with particular reference to the minimum number of samples required to determine background levels within known errors (e.g. Sutherland, 1991). In the case of lake and reservoir sediments, attempts have been made to infer sediment transfer rates and identify sediment sources from the ^{137}Cs profile (e.g. Walling & He, 1993; Foster & Walling, 1994).

Analysis of ^{137}Cs in cultivated and pasture soils and lake sediments in the English Midlands has been incorporated into a long-term research programme which was established in the 1980s in order to determine rates of soil erosion and sediment transport, identify sediment sources and evaluate the use of a range of tracers on active fluvial and deposited lake sediments (cf. Foster *et al.*, 1985, 1986, 1990; Dearing *et al.*, 1986; Grew, 1990). This paper is concerned with four fundamental questions regarding the validity of the ^{137}Cs technique:

(a) What is the magnitude of the error in measuring ^{137}Cs activities?
(b) To what extent do ^{137}Cs inventories vary in uneroding control sites?
(c) To what extent do cultivated soils exhibit deficiencies or surpluses of ^{137}Cs relative to control sites and can these be defined within known statistical probabilities?
(d) To what extent does a study of ^{137}Cs in sites of accumulation (slope foot locations and reservoirs) offer a sensitive method for interpreting erosional processes in the drainage basin?

BACKGROUND

The results presented here focus mainly on research undertaken in the small (2.38 km^2)


(a)
Seeswood Pool
(b)
Nuneaton
31
32
33
91
90
S1
S2
Seeswood Pool
Outflow
152
145
137
130
0 m 500
Sample arable field.
Background inventory site
Building
Stream gauging station
Catchment boundary
Minor road
Contour (m)
Woodland

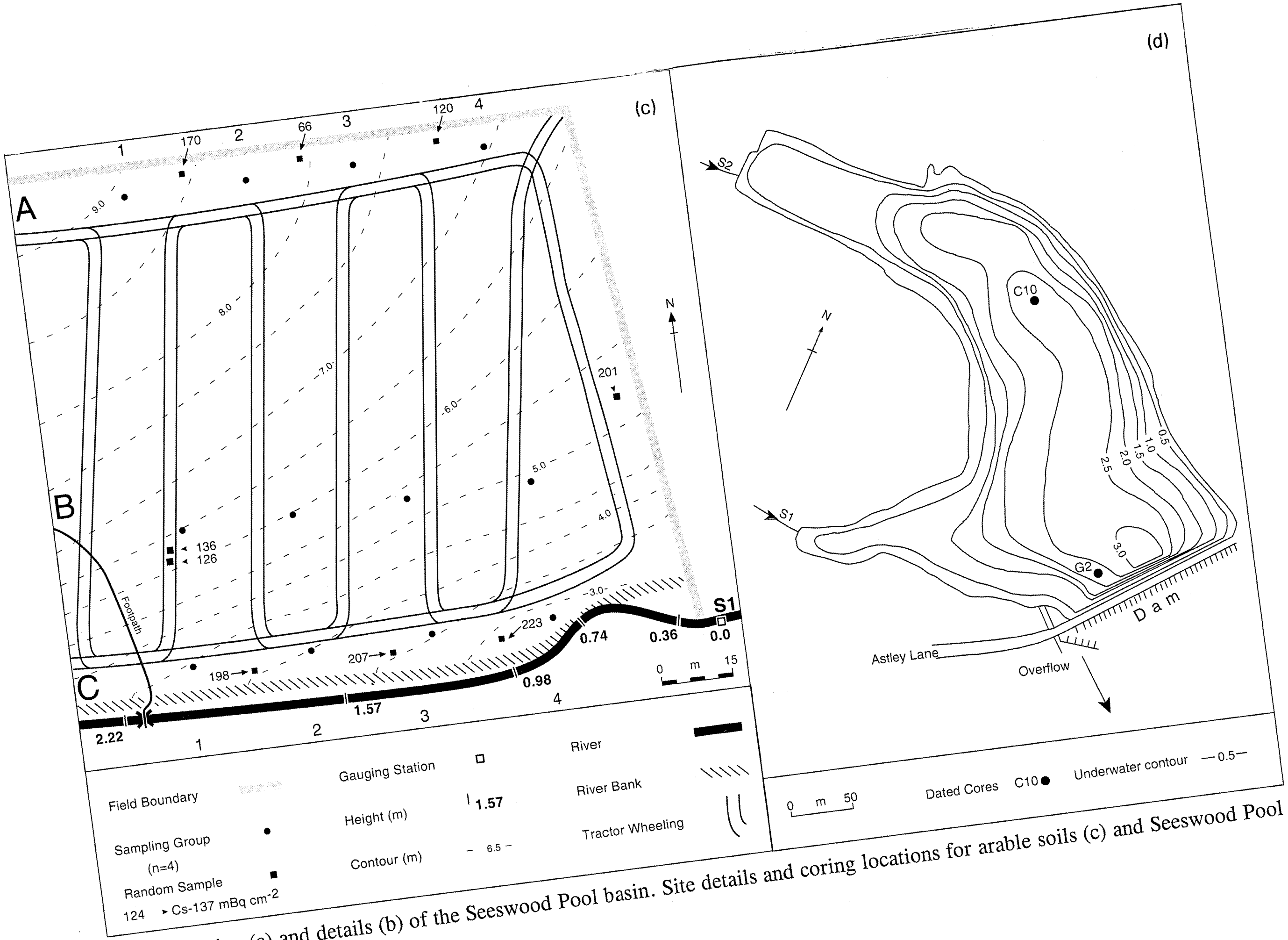


Fig. 1 Location (a) and details (b) of the Seeswood Pool basin. Site details and coring locations for arable soils (c) and Seeswood Pool reservoir sediments (d).

Seeswood Pool Reservoir basin (Fig. 1(a) and (b)) which comprises two sub-basins (S1 and S2; Fig. 1(b)). The gauging station at S1 drains 65.4 ha of arable land (rotational winter wheat and legumes) and S2 drains 161 ha of permanent pasture and grass ley with small areas of woodland.

Two sites were selected for soil sampling (Fig. 1(b)). Part of a cultivated field in the S1 sub-basin has been sampled in order to determine the ^{137}Cs distribution and to quantify the sediment delivery ratio (Fig. 1(c)). A permanent pasture site, approximately 1 km southeast of Seeswood Pool, has been sampled in order to determine the background ^{137}Cs influx. (These fields have a known history and have not been ploughed since the late 1940s). All soil samples were collected with steel core tubes of 26 cm^2 sample area driven vertically into the soil to depths of >40 cm. Two of the 35 lake sediment cores, taken from Seeswood Pool during an earlier part of the research programme, were analysed for ^{137}Cs and ^{210}Pb in order to provide a chronology for calculating sedimentation rates and sediment yields (Foster *et al.*, 1986) (see Fig. 1 for coring locations).

Annual average rainfall for the region is 671 mm (1954-1992) and it is estimated that ^{137}Cs deposition in this region should be similar to that recorded at Chilton, Oxfordshire (*c.* 140 km south of the Seeswood basin) which has an average annual rainfall of 677 mm over the same time period. The ^{137}Cs inventory at Chilton is 161.0 mBq cm^{-2}, decayed to 1992 (Fig. 2(a)). This inventory is similar to that recorded in uneroded Midland soils (see below) and in the sediments of nearby Merevale Lake (158.0 mBq cm^{-2}), which has had low and relatively constant sedimentation rates over the last 130 years (Foster *et al.*, 1985). The average ^{137}Cs inventory for the two cores at Seeswood Pool is 615.7 mBq cm^{-2} (decayed to 1992 and adjusted for sediment focusing over 85% of the lake bed), suggesting a significant influx of ^{137}Cs enriched topsoil.

THE DETECTION SYSTEM AND MEASUREMENT ERRORS

A low efficiency HPGe low energy photon spectrometer (EG&G Ortec planar crystal) was used to measure ^{137}Cs (662 keV). Optimum sample geometries were achieved by compressing *c.* 200 g dry sample (<2 mm soil) to a uniform disc (75 × 24 mm) which was placed in a perspex container. Count times were usually *c.* 48 h in order to obtain acceptable counting errors which were generally around ±13%, at 2 s.d., for soil samples.

The steel core tubes used for sampling had a surface area of *c.* 26 cm^2. Repeat measurements of the surface area of the tubes over the sampling period showed that some damage occurred as a result of sampling stony soils. The maximum error associated with core tube deformation was calculated to be ±5.5%. In total, therefore, an individual ^{137}Cs estimate, in mBq cm^{-2}, is subject to a counting error and sampling area error which, in combination, is ±18.5% (at 2 s.d.). (Results reported in mBq g^{-1} of dry soil are only subject to counting errors.)

VARIABILITY IN BACKGROUND INVENTORIES

Recent studies (e.g. Sutherland & de Jong, 1990; Sutherland, 1991) have shown significant variability in uneroding sites, with coefficients of variation often exceeding

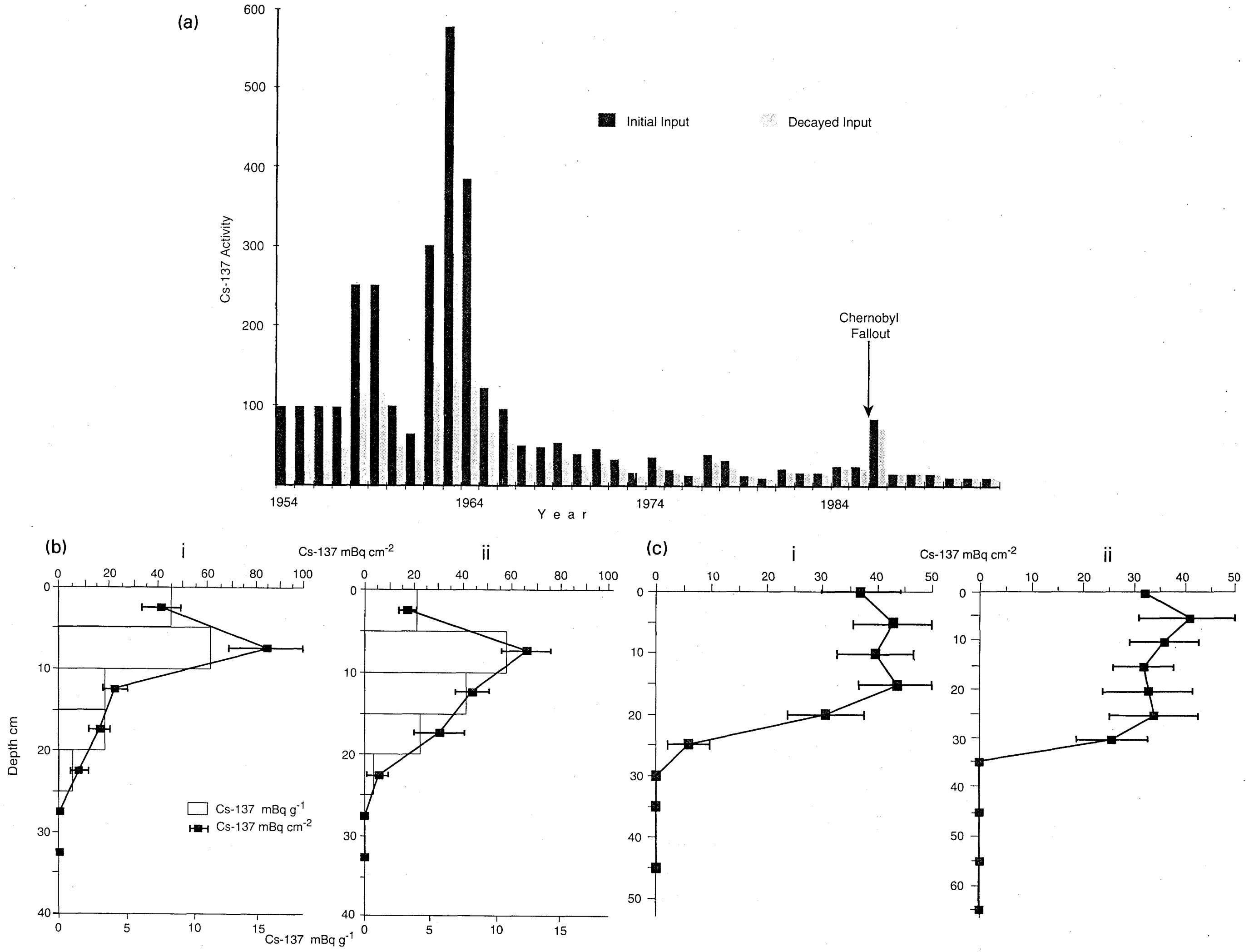


Fig. 2 Observed and decayed atmospheric ^{137}Cs fallout record for Chilton, Oxfordshire (a). ^{137}Cs profiles in uneroding sites (b) and arable soils (c).

Table 1 ^{137}Cs inventories in uneroding sites.

Core site	^{137}Cs activity (mBq cm^{-2})	Count error ± at 2 s.d.
Flat meadow	154.8	28.9
Flat meadow	161.8	34.4
Flat meadow	173.4	39.4
Flat meadow	170.1	39.6
Ridge top	143.4	34.2
Ridge top	143.0	30.9
Furrow base	185.5	40.2
Furrow base	232.9	44.1

30% in forested areas and *c.* 20% in grassland sites. In this study, eight soil cores were taken from undisturbed pasture (Fig. 1(b)) in order to quantify the total ^{137}Cs inventory. Cores were collected in areas where surface gradients were negligible. Like most unploughed sites in the UK (cf. Walling & Bradley, 1990) these profiles show high activities in the near surface samples which rapidly decline down profile (Fig. 2(b)). The tail of the distribution is probably a combined result of bioturbation, diffusion and other convective processes. At all sampling sites, ^{137}Cs was not detected below 30 cm depth and, in most cases, was not detected below 25 cm depth. The cores were collected from a range of microtopographical locations. Four were collected from flat sites but, in the Midlands of England, a common feature of permanent pasture is the presence of ridge and furrow which is believed to be a relict feature of early farming systems. These give a low amplitude rise and fall in the land surface with a wavelength of between 1 and 2 m and an amplitude of 5-15 cm, depending on the degree of preservation. Ridges and furrows generally run normal to the contour. Two samples were collected from each of a ridge top and furrow base (Table 1).

The four flat meadow sites have inventories ranging from 154.8 to 173.4 with a mean of 165.0 mBq cm^{-2} (CV = 10% at 2 s.d.). In contrast, the two ridge-top sites have average inventories of 143.2 mBq cm^{-2} whereas the furrow base has an average inventory of 209.2 mBq cm^{-2}. It is not known whether this difference reflects reworking of deposited ^{137}Cs or a microtopographical control on ^{137}Cs adsorption. Nevertheless, these findings would suggest that some consideration be given to microtopography in designing a suitable sampling scheme since inclusion of data from ridge and furrow sites significantly increases sample variance. The average inventory for all cores is 170.6 mBq cm^{-2} (CV 34.1% at 2 s.d.). The medians for the four sample and eight sample grouping of data in Table 1 are both 166.0, with no statistically significant differences between the two groups at the 95% confidence level (Mann-Whitney U test). It is therefore suggested that a value of 166 mBq cm^{-2} is a meaningful estimate of background ^{137}Cs influx and that, since cultivated land does not exhibit distinctive ridge and furrow topography, the lower CV of 10% is a more appropriate estimate.

VARIABILITY IN ^{137}Cs ON CULTIVATED FIELDS

Soil cores were collected from the cultivated field shown in Fig. 1(c). At twelve sites on three transects (labelled A to C by row and 1 to 4 by column), four cores were collected at the corners of a randomly oriented 0.25 m^2 quadrat. Other sites were sampled systematically in order to include parts of the field, including tractor wheelings, omitted by the grid sampling (^{137}Cs activity data for single cores is given on Fig. 1(c)).

^{137}Cs has a different distribution in cultivated soil profiles from the pasture sites. The two profiles of Fig. 2(c) show that ^{137}Cs is relatively uniformly distributed with depth to the plough layer, with no detectable ^{137}Cs below 30 cm. For the 12 replicated coring sites, the mean, median and standard deviation were calculated (Table 2).

Table 2 Mean, median and standard deviation of ^{137}Cs activity (mBq cm^{-2}) of four cores from each coring location on the sample grid.

Row		Column: 1	2	3	4
A	Mean	197.0	173.5	149.5	151.5
	Median	204.0	184.5	149.5	159.0
	St. dev.	(19.24)	(32.83)	(16.18)	(28.11)
B	Mean	178.8	159.5	144.3	168.8
	Median	177.0	164.5	157.0	172.5
	St. dev.	(15.33)	(19.02)	(36.34)	(22.20)
C	Mean	147.75	190.3	198.5	201.3
	Median	144.5	189.0	200.0	195.0
	St. dev.	(17.35)	(10.05)	(25.70)	(23.51)

Meaningful comparison of these field data with background inventories requires careful selection of the most appropriate statistical technique, particularly since sample sizes are small and a comparison of mean and median values suggests that individual site data are not normally distributed, even though the total inventories of the 57 cores do approximate a normal distribution (chi-squared test at 95% significance level). For the 57 cores, there is no statistically significant difference between the average ^{137}Cs inventory and the background inventory, suggesting no significant loss of ^{137}Cs, or soil, from the field.

Comparison between the three rows of sampled cores suggests that the only significant differences are between rows A and C and B and C, with median values of 167.5, 166.0 and 183.0 mBq cm^{-2} for rows A, B, and C respectively. The ^{137}Cs activity of row C cores is significantly higher than the background input at the 95% confidence level (one tailed Mann-Whitney U test). However, samples from rows A and B are not significantly different from the stable site inventories. Comparison of group medians by row and cell with the atmospheric influx, again using the Mann-Whitney U test, shows that cells A1 and B1 are significantly higher at the 90% level and cells C2, C3 and C4 are significantly higher at the 95% level. The Mann-Whitney U test can also be used to compare individual samples with a group median. The probabilities are, of course, much lower but two of the additional sites adjacent to the hedge boundary at the slope head have an 80% probability of having a lower inventory than the control site and, for the two cores collected in a tractor wheeling, the probability of a significantly lower inventory rises to 93%. Conversely the single cores collected at the base of the field all have an 80% probability of being higher than the background control.

Of particular significance is the ^{137}Cs deficit in cores taken from tractor wheelings, four pairs of which run down the cultivated slope. After severe storms in December 1989, these were calculated to supply *c.* 640 kg of sediment to the lower slope area through small rills which formed at the base of each of the wheelings. The ^{137}Cs activity and soil bulk density in these cores averages 3.87 mBq g^{-1} and 1.4 g cm^{-3} respectively. From these data, it is calculated that this single storm removed 25×10^5 mBq of ^{137}Cs from an area of *c.* 6000 m^2; equivalent to an inventory of 0.041 mBq cm^{-2} from the whole area. This is an insignificant proportion of the total ^{137}Cs inventory on these eroding sites. Concentrating this soil at the slope base over an area of *c.* 350 m^2, and assuming no ^{137}Cs loss from the field, adds 0.706 mBq cm^{-2}. This small area of focused deposition is therefore *c.* 17 times more sensitive than the eroding sites. If all soil redistribution occurs as a result of erosion from tractor wheelings, it is calculated that in order to increase slope foot inventories to *c.* 200 mBq cm^{-2}, 45 events of similar magnitude would be required in the 38 years since ^{137}Cs was first deposited; i.e. just over one event per year.

These calculations have important implications for the sensitivity of the ^{137}Cs technique and for the comparison of whole field inventories with background sites. As demonstrated in this and other studies (cf. Walling & Bradley, 1990) the proportion of a field occupied by eroding sites is usually much larger than the area occupied by sites of deposition and whole field inventories may be biased as a result of varying sensitivities across the whole slope, particularly if a disproportionately large number of cores is taken from sites of accumulation.

LAKE SEDIMENT INVENTORIES

The lake sediment ^{137}Cs profile for core G2 (Fig. 1(d)) is given in Fig. 3 along with the sediment yield record for the post 1954 period. Unlike the atmospheric record (Fig. 2(a)), high levels of ^{137}Cs activity are sustained upcore of the 1963 peak which would suggest continuing delivery of ^{137}Cs with eroded basin soils (Fig. 3(a)). The ^{137}Cs inventory is 656.2 and 792.2 mBq cm^{-2} for cores C10 and G2 respectively, suggesting some focusing or particle size associated enrichment with increased distance from the inflow. Activities in the upper 10 cm (1978-1982) average 5.10 mBq g^{-1} and mostly lie within ±2 s.d. of arable soils. The upper 10 cm of undisturbed pasture soils averages 8.83 ± 2.7 mBq g^{-1} at 2 s.d. Average concentrations for the reservoir sediments deposited during the periods 1973-1977 and 1965-1976 are 5.10 and 7.00 mBq g^{-1} respectively. In the earlier period the activities are closer to those of pasture topsoils.

It has been demonstrated from basin monitoring (Foster *et al.*, 1990; Grew, 1990) that *c.* 90% of the post 1978 sediment in the reservoir derives from the pasture (S2) sub-basin and that little soil transfer takes place between the arable fields and the S1 stream. The generally declining ^{137}Cs concentrations in the reservoir sediment after 1965 could therefore be attributed to the depletion of ^{137}Cs enriched topsoils from pasture sites due to overgrazing and heavy poaching of the riparian zone, i.e. resulting from an exhaustion of ^{137}Cs in these areas which have a minimal atmospheric influx today. Expansion of the area contributing ^{137}Cs enriched pasture topsoils to the lake would be

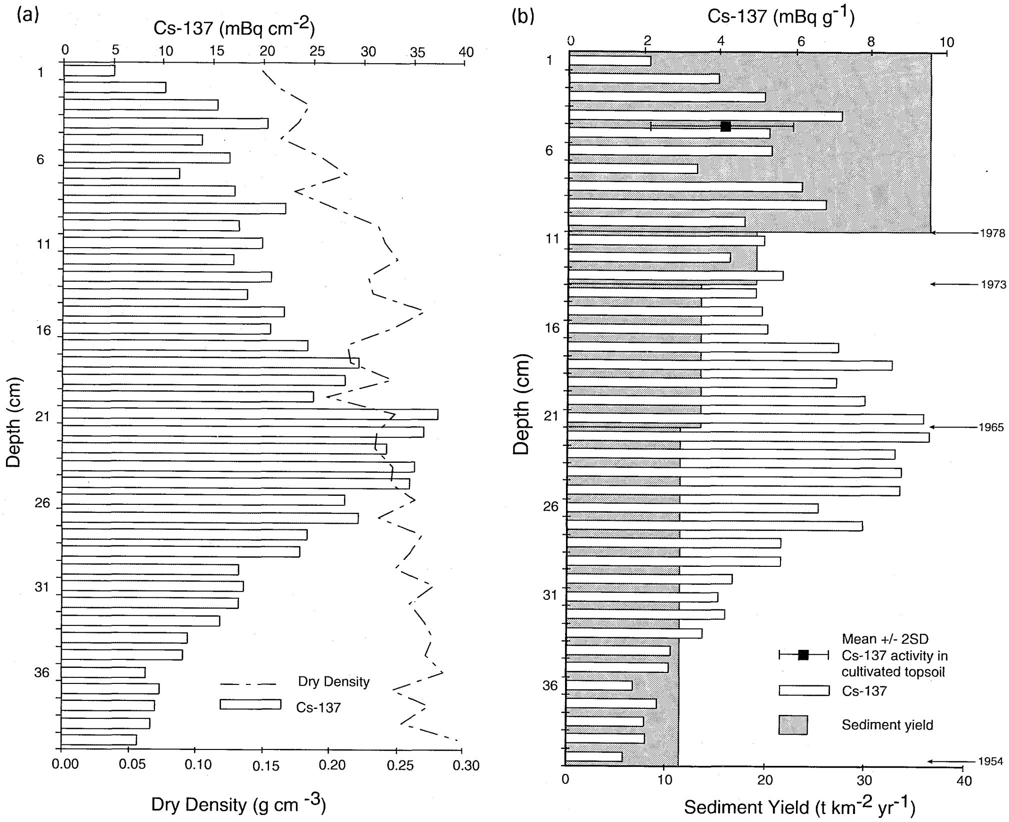


Fig. 3 The ^{137}Cs record in Core G2 of Seeswood Pool. ^{137}Cs activity in mBq cm^{-2} (a); sediment yields, ^{137}Cs concentration (mBq g^{-1}) and the variability in arable topsoil concentrations (b). (^{137}Cs concentrations in (b) are corrected for autochthonous contribution to the reservoir sediment which averages 34% in the upper 40 cm; Foster *et al.*, 1986).

expected to produce an increase in ^{137}Cs concentration (e.g. at 4 cm depth in the sediment core). A significant increase in channel bank erosion would be expected to reduce ^{137}Cs concentrations (e.g. at 1 cm depth in the sediment core).

DISCUSSION

In relation to the four questions posed in the introduction, it is tentatively concluded that the sampling and measurement error in determining a single ^{137}Cs activity per unit area in a soil sample is around 18% and that the variability in background uneroding sites is around 10%. The inherent variability in the ^{137}Cs activity of arable soils makes discrimination between eroding and control sites difficult, particularly with respect to calculating rates of soil movement and estimating the sediment delivery ratio for the field. It has also been shown that sites of deposition at the slope foot are some 17 times more sensitive to ^{137}Cs redistribution than sites of erosion.

Reservoir sediments integrate basin erosional, sediment transport and delivery processes and appear to provide a high degree of sensitivity to basin disturbance. However, a ^{137}Cs based interpretation of sediment sources in this basin is complicated by the possible disturbance and expansion of the pasture sites which, from recent monitoring, appear to be the dominant sediment sources.

Acknowledgements The authors would like to thank Professor D. Walling and Mr P. Owens for commenting on an earlier draft of this paper, Ruth Gaskell who drew the diagrams and AERE Harwell for providing atmospheric ^{137}Cs data.

REFERENCES

Dearing J. A., Morton, R. I., Price, T. W. & Foster, I. D. L. (1986) Tracing movements of topsoil by magnetic measurements. *Phys. Earth. Planet. Inter.* **42**, 93-104.

Foster, I. D. L., Dearing, J. A., Simpson, A., Carter A. D. & Appleby, P. G. (1985) Lake catchment based studies of erosion and denudation in the Merevale basin, Warwickshire, UK. *Earth Surf. Processes & Landforms* **10**, 45-68.

Foster. I. D. L., Dearing, J. A. & Appleby, P. G. (1986) Historical trends in catchment sediment yields: a case study in reconstruction from lake-sediment records in Warwickshire, UK. *Hydrol. Sci. J.* **31**(3), 427-443.

Foster, I. D. L., Grew, R. & Dearing, J. A. (1990) Magnitude and frequency of sediment transport in agricultural basins: a paired lake-catchment study in Midland England. In: *Soil Erosion on Agricultural Land* (ed. by J. Boardman, I. D. L. Foster & J. A. Dearing), 153-171. John Wiley, Chichester, UK.

Foster, I. D. L. & Walling, D. E. (1994) Using reservoir sediment deposits to reconstruct sediment yields and sources in the catchment of the Old Mill reservoir, South Devon, UK, over the past 50 years. *Hydrol. Sci. J.* **39**(4), 347-368.

Grew, R. G. (1990) Sediment yields and sources over short and medium timescales in a small agricultural catchment in N. Warwickshire, UK. Unpublished PhD Thesis, Coventry University, Coventry, UK.

Loughran, R. J., Campbell, B. L. & Elliott, G. I. (1990) The calculation of net soil loss using ^{137}Cs. In: *Soil Erosion on Agricultural Land* (ed. by J. Boardman, I. D. L. Foster & J. A. Dearing), 119-126. John Wiley, Chichester, UK.

Peart, M. & Walling, D. E. (1988) Techniques for establishing suspended sediment sources in two drainage basins in Devon, UK: a comparative assessment. In: *Sediment Budgets* (Proc. Porto Alegre Symp., December 1988), 269-279. IAHS Publ. no. 174.

Sutherland, R. A. (1991) Examination of caesium-137 areal activities in control (uneroded) locations. *Soil Technol.* **4**, 33-50.

Sutherland, R. A. & de Jong, E. (1990) Quantification of soil redistribution in cultivated fields using caesium-137, Outlook, Saskatchewan. In: *Soil Erosion – Experiments and Models* (ed. by R. B. Bryan), 177-194. Catena Supplement no. 17, Cremlingen-Destedt, Germany.

Walling, D. E. & Bradley, S. B. (1990) Some applications of caesium-137 measurements in the study of erosion, transport and deposition. In: *Erosion, Transport and Deposition Processes* (Proc. Jerusalem Workshop, March-April 1987), 179-203. IAHS Publ. no. 189.

Walling, D. E. & He, Q. (1993) Towards improved interpretation of Cs-137 profiles in lake sediments. In: *Geomorphology and Sedimentology of Lakes and Reservoirs* (ed. by J. McManus & R. W. Duck), 31-53. John Wiley, Chichester, UK.