A Caesium-137 budget approach to the investigation of sediment delivery from a small agricultural drainage basin in Devon, UK

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ABSTRACT The potential for using a Caesium-137 budget for a small drainage basin to elucidate the pattern of sediment delivery and more particularly the relative importance of erosion, deposition and sediment yield is introduced. Preliminary results of applying this approach to a small agricultural drainage basin are reported. These indicate an overall sediment delivery ratio for the cultivated portion of the basin of 3.5 percent. Within this zone it is estimated that the sediment delivery ratio associated with erosion and redistribution of sediment in the cultivated fields is 48 percent and that only 7.2 percent of the material transported from the fields reaches the catchment outlet. Suggestions for developing the approach further are advanced.

INTRODUCTION

In a recent paper, Walling (1983) pointed to the importance of an improved understanding of the processes of sediment delivery interposed between on-site erosion and sediment yield at the outlet of a drainage basin and to the need for further investigations of this aspect of drainage basin behavior. One of the major problems facing such investigations is the lack of existing measurement techniques capable of documenting the deposition, storage and remobilization of sediment within the drainage basin conveyance system. Virtually all values of sediment delivery ratio available in the literature are, for example, only tentative estimates based on a comparison of measured downstream sediment yield with an estimate of gross upstream erosion. The latter is commonly derived from an estimate of sheet erosion produced by a soil loss equation such as the USLE, corrected to take account of additional contributions from channel and gully erosion, and is therefore open to considerable uncertainty.

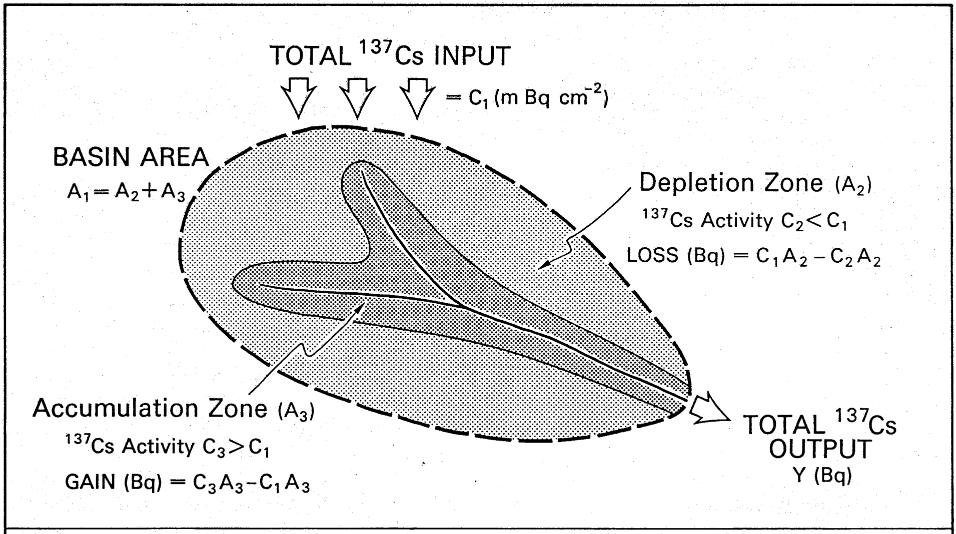
One approach to the study of erosion and deposition within a basin which may, however, offer considerable potential for elucidating delivery processes is the use of Caesium-137 (^{137}Cs) as a natural tracer of soil and sediment movement. Caesium-137 is present in the environment only as a product of the atmospheric testing of nuclear devices during the late 1950s and early 1960s and fallout of this environmental radioisotope was first documented in 1954. Rates of fallout reached a maximum in 1964 and declined rapidly after the nuclear test ban treaty (cf. Ritchie et al., 1975; Pennington et al., 1976). Existing evidence indicates that on reaching the soil surface as fallout, ^{137}Cs is rapidly and strongly adsorbed in the upper horizons of the soil and that further downward translocation by physico-chemical processes is limited (cf. Tamura, 1964). Subsequent movement of ^{137}Cs is therefore associated with the erosion, transport and deposition of sediment particles (e.g. Rogowski & Tamura, 1970a, b; Campbell et al., 1982). Caesium-137 has a half-life of 30.1 years and approximately 60 percent of the total input of this radioisotope since fallout began in 1954 could still remain within the system. Considerable potential therefore exists for studying the movement of sediment within a drainage basin over the last 30 years, by measuring the distribution of ^{137}Cs within its soils.

In their pioneering studies, McHenry & Ritchie and their co-workers demonstrated how estimates of total input of ^{137}Cs to several basins in southeastern USA were consistent with the levels remaining in their soils and deposited in downstream reservoirs (e.g. McHenry & Ritchie, 1975; Ritchie et al., 1974). This work was subsequently extended to study patterns of erosion and deposition along slope transects within the White Clay Lake Watershed in Wisconsin, USA (e.g. McHenry & Ritchie, 1977; McHenry et al., 1978). In this application, levels of total ^{137}Cs activity within the profile were measured at several points along the transect and compared with an estimate of the overall input. Depletion indicated erosion, whilst deposition was marked by enhanced ^{137}Cs levels. Other researchers have developed the approach further. For example, Longmore et al. (1983) have used measurements of the areal concentration of ^{137}Cs to map the major areas of soil erosion and deposition within an upland catchment on the Darling Downs, Australia, and Loughran et al. (1982) report studies of sediment movement within a small drainage basin in the Hunter Valley, New South Wales, Australia, based on ^{137}Cs measurements. Brown et al. (1981a, b) were perhaps the first to extend such studies to consider the overall behavior of a drainage basin. They estimated erosion rates within two small basins (6 and 12.9 ha) located in the Willamette Valley, Oregon, USA, by surveying the volume and mass of soil residing in depositional zones and coupling these values with an estimate of the sediment delivery ratio. De Jong et al. (1983) report a similar analysis of erosion and deposition within eight small basins in the Canadian Prairies.

Similar work undertaken by the authors in several small drainage basins in Devon, UK has suggested that considerable scope exists to extend the application of these techniques further, in order to investigate sediment delivery from a drainage basin and to provide an estimate of the importance of sediment redistribution and therefore of its sediment delivery ratio. This extension involves the establishment of a ^{137}Cs budget for a basin, incorporating estimates of inputs, losses, redistribution and output, which may be used as a basis for studying the erosion, deposition and output of sediment. There have been some previous attempts to derive ^{137}Cs budgets (McHenry & Ritchie, 1975) and balances (De Jong et al., 1983) for drainage basins, but these have not considered outputs and the relative importance of erosion and deposition at the basin scale. Bazzoffi & Panicucci (1983) also describe a ^{137}Cs budget for a small drainage basin - reservoir system in Central Italy, but this again was primarily concerned with reservoir inputs rather than erosion and redistribution of sediment within the basin.

THE BUDGET APPROACH

The basis of the approach introduced above is depicted in Fig. 1. Essentially, it involves evaluation of the total ^{137}Cs input to the basin, the total ^{137}Cs loss from the area experiencing erosion, the total gain of ^{137}Cs in areas evidencing deposition and the total output of ^{137}Cs from the basin, for the period 1954 to the present. The two budget equations listed in Fig. 1 provide a means of establishing the consistency of the values obtained and the delivery ratio may be calculated by comparing either the relative magnitude of gross and net (gross-deposition) losses or of output and gross loss (Fig. 1). The



BUDGET

LOSS − GAIN = OUTPUT

INPUT $(C_1A_1) = C_2A_2 + C_3A_3 + Y$

SEDIMENT DELIVERY RATIO = LOSS − GAIN / LOSS
or OUTPUT / LOSS

Figure 1

results may in turn be extrapolated to the associated soil and sediment to provide an assessment of the sediment budget of the drainage basin.

Figure 1 provides an idealized example of a ^{137}Cs budget for a drainage basin. In reality there may not be a simple and clear spatial differentiation of the zones of loss and accumulation, since areas of both erosion and deposition may occur within individual fields. However, the basis of the budget approach is still applicable. Furthermore, it can be applied to constituent areas of the basin to provide a more detailed evaluation of the pattern of sediment delivery. This paper provides some preliminary results of the application of the ^{137}Cs budget approach to a small drainage basin in Devon, UK.

THE STUDY BASIN

The study basin, known as the Yendacott basin, has a drainage area of 1.6 km^2 and its general form is illustrated in Fig. 2. It is developed on sandstones, breccias and conglomerates of Permian age and the soils are dominated by gleyed brown earths of the Rixdale series, with some brown earths of the Shaldon series occurring around the western margins. Some small pockets of soils belonging to the Cutton series, developed on coarse alluvium and colluvium, also occur in the valley bottoms. Topography is generally subdued with slope angles rarely exceeding 5°. Approximately 14 percent of the area is covered by mixed deciduous woodland, largely in the valley bottom areas. Over the remainder of the basin, the fertile soils and favorable topography have encouraged the establishment of arable cultivation which is dominated by cereal crops (wheat and barley) grown in rotation with ley grass, fodder beans and potatoes. The individual fields, which are frequently bounded by hedges and banks, are characteristically of the order of 12 ha in size. As a result of the unfavorable drainage characteristics of the soils of the Rixdale series, sub-surface tile drainage and ditches have been introduced into several parts of the basin.

Mean annual precipitation is estimated at 800 mm whilst mean annual runoff from the basin is approximately 350 mm. More than 50 percent of the mean annual precipitation falls during the months of November to March when many of the fields which are traditionally tilled in the autumn have limited vegetation cover. Measurements of suspended sediment yield have been undertaken at the outlet of the basin on an intermittent basis since 1975. Suspended sediment concentrations sampled during storm events are typically high by local standards and may exceed 3000 mg l^{-1} during periods of intense rainfall. The long term mean annual suspended sediment yield of the basin is approximately 55 tkm^{-2}. The suspended sediment load is dominated by clay- and silt-sized fractions, with these commonly accounting for about 75 percent and 20 percent respectively of the total load.

Suspended sediment yields in this and other adjacent basins in the local area must be seen as low by world standards (cf. Walling & Webb, 1983) and this has generally been attributed to the low rainfall erosivity, the limited surface runoff and the good vegetation cover. However, the increasing incidence of arable cultivation involving autumn tillage must be seen as providing conditions more favorable for soil erosion. It has therefore also been suggested that the low sediment yields reflect, at least in part, low sediment delivery ratios associated with the landscape of relatively small fields. These uncertainties afforded additional justification for an attempt to apply the ^{137}Cs budget approach within the study basin.

DATA COLLECTION

An initial attempt to document the magnitude of erosion and deposition within the Yendacott basin has focussed on four fields in the southeast of the basin (Fig. 2). Measurements of ^{137}Cs activity within the soil profile have been made at several sites within these fields selected as representative of the depletion and accumulation zones depicted on Fig. 1. Samples were collected from an area of 800 cm^2 at 2 cm increments down to 50 cm using the procedure employed by Campbell and Loughran (personal communication). This sampling was supplemented by a grid of 70 sites distributed uniformly over the four fields where whole-core samples (42 cm^2) were collected to a depth of approximately 60 cm using a steel percussion corer. In addition, both whole-core and down-profile samples were collected from several sites within the near vicinity of the study basin, which were characterized by hilltop locations, minimal slopes, and permanent pasture undisturbed by cultivation. These may be equated with the 'input sites' of Campbell et al. (1982) and the control sites of De Jong et al. (1983) and provide an estimate of the total or baseline input of ^{137}Cs to the basin.

All soil samples were subsequently air dried, disaggregated and sieved to separate the < 2 mm fraction. a representative sub-sample of this fraction (ca. 1 kg) was packed into a 1 l perspex Marinelli beaker prior to analysis. Caesium-137 activity of the sub-samples was measured by gamma spectrometry using a Canberra Series 35 multi-channel analyzer linked to a germanium detector housed in a lead shield. Count times were typically of the order of 30000s, providing an analytical precision of within + 5 percent. Results were calculated according to the surface area of the original sample in units of $mBqcm^{-2}$.

Bulk samples of suspended sediment have been collected at the basin

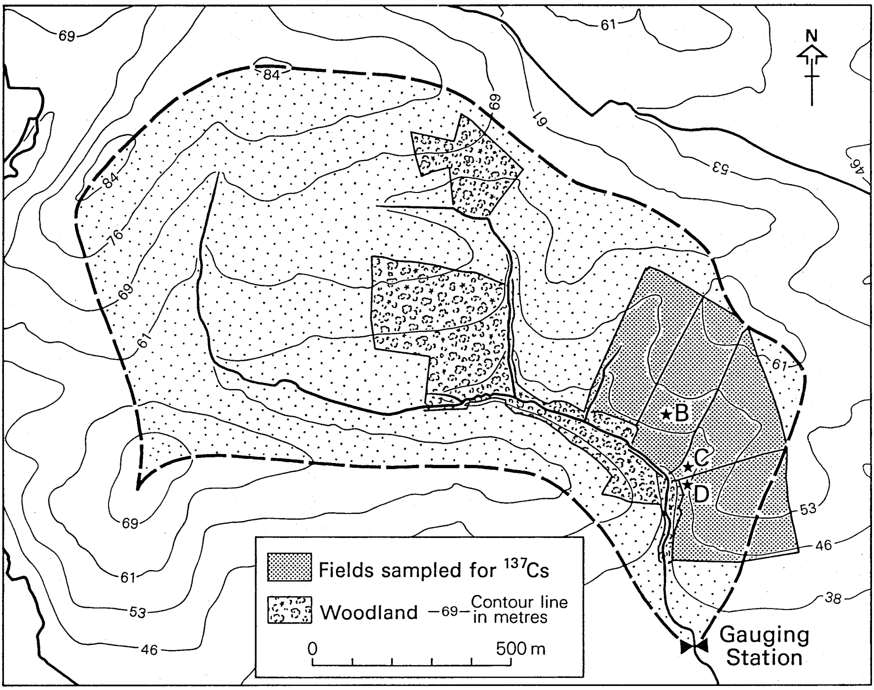


Figure 2

outlet under a variety of flow conditions during the period 1982 to present in order to measure the ^{137}Cs content of suspended sediment transported from the basin. In view of the relatively low concentrations (250-3000 mgl^{-1}) encountered during storm events and the need to obtain appreciable quantities of suspended sediment ($>$20 g), 100 l samples of river water were collected using a pump sampler and transported to the laboratory where a continuous flow centrifuge was used to recover the sediment. This was freeze dried prior to analysis.

RESULTS

The field scale

Measurements of ^{137}Cs activity at five 'input sites' provided consistent estimates of an average baseline input level of 320 mBqcm^{-2}. This is in close agreement with the findings of Cambray et al. (1982) who suggested that the magnitude of ^{137}Cs input over the UK was closely controlled by mean annual precipitation. The representative profile for an input site illustrated in Fig. 3A evidences the typical down-profile distribution of ^{137}Cs described by other workers, with the majority of the radioisotope being contained in the top 10 cm and an exponential decrease occurring below.

Profiles excavated within the four fields used for detailed sampling showed clear evidence of the influence of cultivation and of erosion and deposition. The profile illustrated in Fig. 3B was obtained near the middle of one of the fields (site B, Fig. 2) and in this case the almost uniform levels of ^{137}Cs recorded down to 30 cm may be ascribed to mixing by cultivation within the plough layer (which extends down to approximately 30 cm). The total ^{137}Cs content of 273 mBqcm^{-2} recorded

Table 1 Caesium-137 content of cores collected from the four study fields

	Depletion (< 320 MBqcm^{-2})	Gain (> 320 mBqcm^{-2})
Number of cores	45	25
% cores	64	36
Average ^{137}Cs content	226 mBqcm^{-2}	408 mBqcm^{-2}
Standard deviation	65 mBqcm^{-2}	75 mBqcm^{-2}

Gross erosion averaged over 70 sites = 61 mBqcm^{-2} = 19% baseline input
Deposition averaged over 70 sites = 32 mBqcm^{-2} = 10% baseline input
Loss from fields averaged over 70 sites = 29 mBqcm^{-2} = 9% baseline input

for this profile is also significantly less than the input baseline of 320 mBqcm^{-2}, suggesting that some erosional loss of ^{137}Cs has occurred. profiles taken towards the base of the slopes (sites C and D Fig. 2) evidence the existence of ^{137}Cs to greater depths than the 30 cm plough layer and total levels of ^{137}Cs considerably in excess of the input baseline (Fig. 3C and D). Both features point to depositional gains of ^{137}Cs which are consistent with the location of the sites of these profiles near the base of a slope.

Comparison of the values of ^{137}Cs activity obtained for the grid of 70 whole-cores with the input baseline of 320 mBqcm^{-2} provides a means of obtaining estimates of the magnitude of erosional losses and depositional gains of ^{137}Cs over the four study fields. Forty-five or 64 percent of the core sites evidenced depletion of ^{137}Cs, whilst the remaining 25 sites (36 percent) exhibited accumulation (Table 1). Sites evidencing erosional losses were predominantly located in middle and upper areas of the slopes, whilst sites evidencing depositional gains generally occurred towards the base of the slopes. However, no simple pattern existed and a more intensive sampling program would be required to decipher the detailed distribution. This undoubtedly reflects the intricate pattern of soil saturation and surface runoff generation during storm events (cf. Burt et al., 1983) rather than more traditional concepts of sheet erosion which emphasize the importance of upslope length.

If the average levels of ^{137}Cs associated with depletion and accumulation sites are calculated (Table 1), these may be used to estimate the relative importance of erosional losses and depositional gains of ^{137}Cs over the sampled slopes. The average ^{137}Cs activity of the 45 eroded sites of 226 mBqcm^{-2} represents an overall loss of 19 percent of the baseline or input ^{137}Cs associated with the total 70 sites. Approximately 52 percent of this loss may, however, be accounted for by deposition at the 25 accumulation sites, whilst 48 percent must be viewed as output from the system. The delivery ratio based on these estimates is therefore 48 percent, indicating that approximately one half of the ^{137}Cs eroded during the period 1954-1985 has been redeposited within the study fields.

It is, however, important to recognize that the above results relate to the grid of sample sites which in turn essentially represent within field conditions. Field evidence and the characteristics of the ^{137}Cs profiles obtained from sites C and D (Figs. 2 and 3) suggest that a considerable volume of deposition may occur at the base of the slopes in

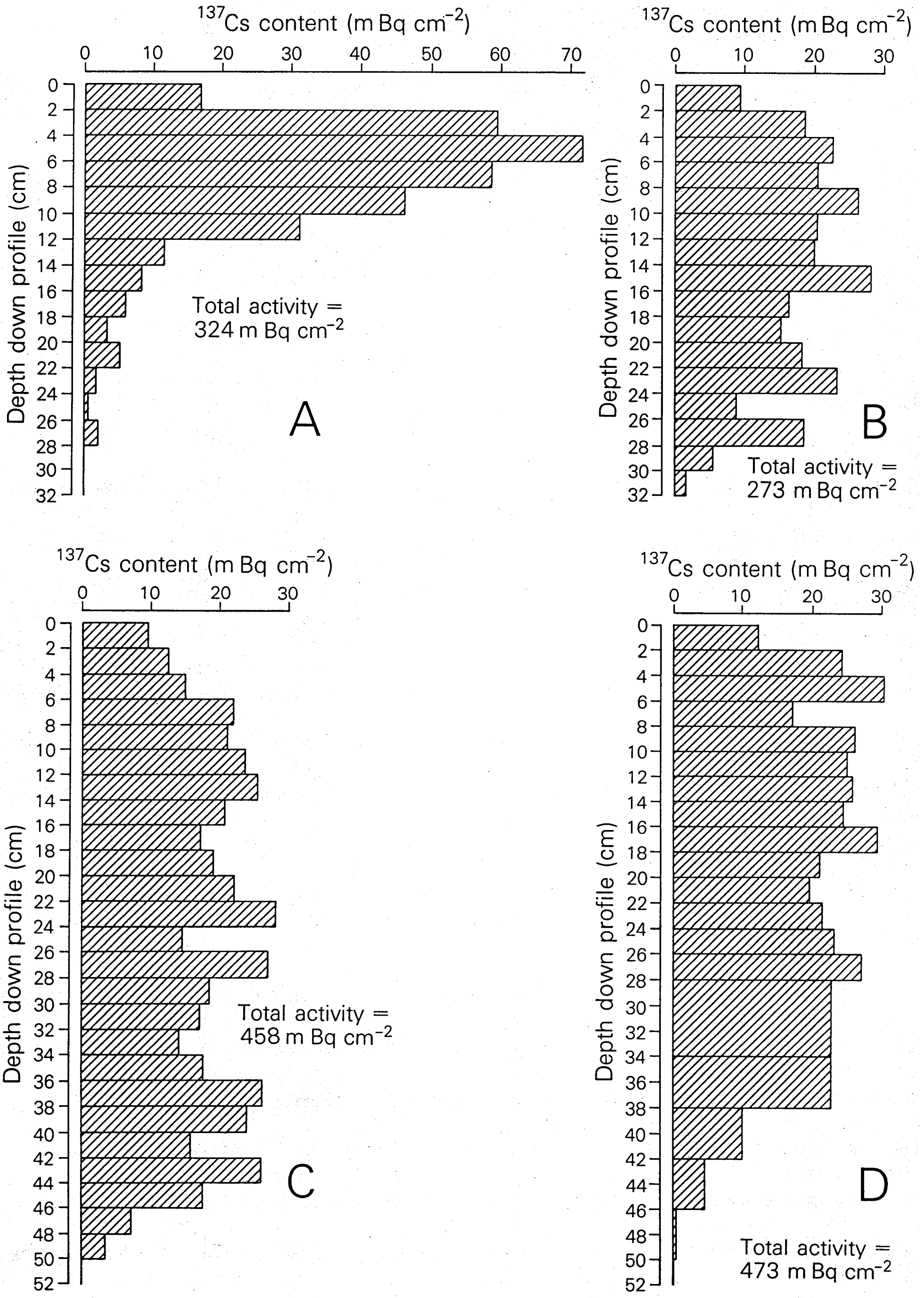


Figure 3

close proximity to the field boundaries and associated with the plough headlands and the rough pasture of the bottomlands bordering the stream. This is inadequately represented by the coarse sampling grid employed in this study and the amount of ^{137}Cs and associated sediment leaving the fields and entering the stream is likely to be considerably less than suggested above.

The basin scale

In the absence of a complete inventory of ^{137}Cs depletion and, more particularly, accumulation for the Yendacott basin, it is not possible to estimate the overall sediment delivery ratio for the basin as proposed in Fig. 1. However, comparison of the output of ^{137}Cs from the basin with an estimate of erosional losses obtained from the measurements undertaken in the four study fields can provide some indication of the magnitude of this ratio.

It is clearly impossible to obtain a direct estimate of the total output of ^{137}Cs associated with the sediment yield from the study basin, since this would require detailed measurements of the ^{137}Cs content of the sediment and of sediment yield for the period 1954 to present. However, it is suggested that a meaningful estimate can be obtained by making a number of assumptions.

Results presented elsewhere for the larger Jackmoor Brook basin (9.8 km^2), which incorporates the Yendacott basin, (Peart & Walling, 1986), suggest that the cultivated fields provide the dominant source of suspended sediment. Furthermore, the ^{137}Cs levels associated with suspended sediment were found to be closely similar to those in topsoil, when due allowance was made for the enrichment of the former in fines. In the case of the Yendacott basin, measurements of the ^{137}Cs concentration in 25 bulk samples of suspended sediment representing a wide range of storm-period conditions during the period 1982-5 provided an average value of 14.8 mBqg^{-1}. This value is entirely consistent with the data presented in Fig. 2B, C and D for the topsoil of arable fields. For example, it is assumed from Fig. 2 that the average ^{137}Cs activity in a 2 cm slice of cultivated topsoil is 22 mBqcm^{-2}, and that a bulk density of 1.2 gcm^{-3} is typical, the concentration of Cs in topsoil would be of the order of 9.2 mBqg^{-1}. The enrichment factor of 1.6 necessary to equate this concentration for cultivated topsoil (9.2 mBqq^{-1}) with that for suspended sediment (14.8 mBqg^{-1}) conforms closely to that proposed by Peart & Walling (1986) and accords with the documented enrichment of the suspended sediment in fines.

If it is accepted that the annual output of ^{137}Cs from the study basin associated with suspended sediment may be represented as the product of annual sediment yield and the contemporary ^{137}Cs concentration in cultivated topsoil adjusted by an enrichment factor of 1.6, total output for the period 1954 to the present may be calculated. The ^{137}Cs concentration in cultivated topsoil during each year of this period has been estimated from data on annual ^{137}Cs fallout. Values of annual ^{137}Cs fallout were available for Milford Haven (Cambray, personal communication) located 150 km to the north of the study area and receiving a similar annual precipitation. The total ^{137}Cs fallout at Milford Haven decayed to 1985, is equivalent to 304 mBqcm^{-2}, and this value is close to the baseline input activity of 320 mBqcm^{-2} assumed for the study basin in 1985. The annual ^{137}Cs fallout data for Milford Haven (Fig. 4A), adjusted by the ratio 320/304, have therefore been used as representative of the Yendacott basin.

The accumulated ^{137}Cs inputs for each year, adjusted for radioactive decay, provide annual estimates of the total ^{137}Cs within the soil during the period 1954 to present. If this cs activity is assumed to be uniformly distributed throughout the 30 cm plough layer with a bulk density of 1.2 gcm^{-3}, the ^{137}Cs content in the cultivated topsoil can be

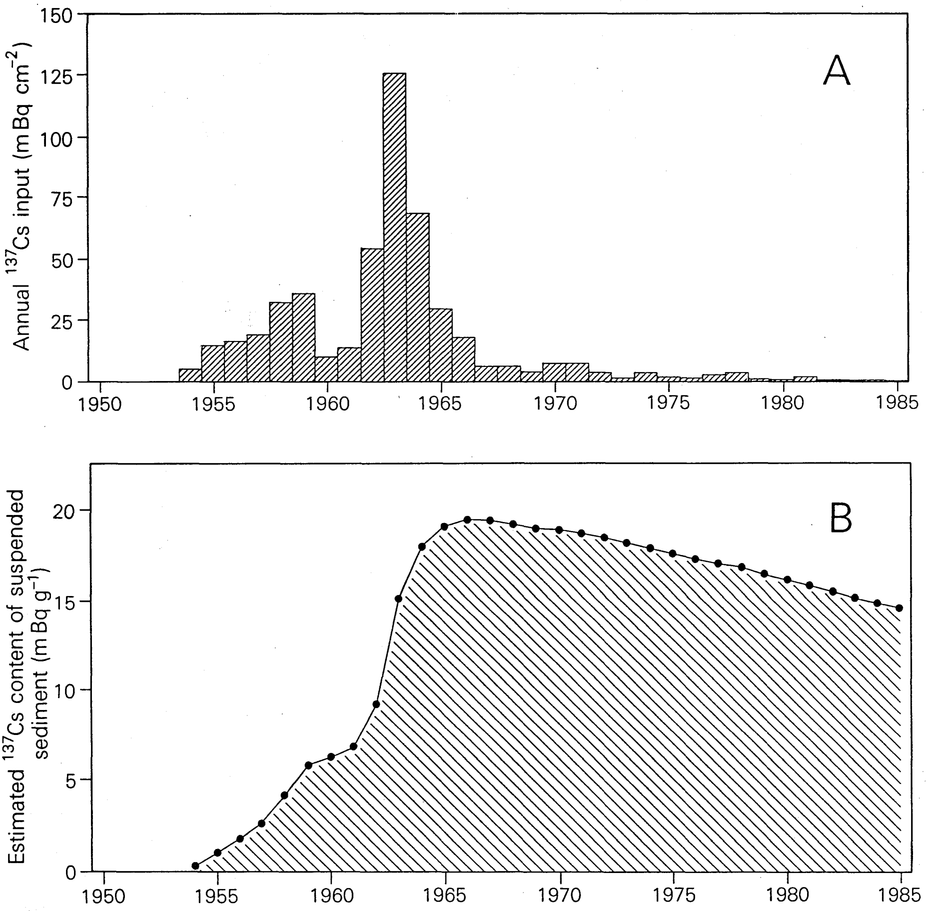


Figure 4

calculated. This can in turn be converted to an estimate of the ^{137}Cs concentration in suspended sediment by applying the enrichment factor of 1.6 previously defined. Figure 3B plots the estimated ^{137}Cs concentration in suspended sediment transported from the study basin during the period 1954 to present, calculated using the above procedure. The values depicted in Fig. 4B could be viewed as slight overestimates since the procedure takes no account of the effects of erosion in depleting the ^{137}Cs activity within the soil as time proceeds. However, this effect is considered to be of limited importance when compared with the other generalizations involved in the calculation procedure.

The annual outputs of ^{137}Cs associated with the suspended sediment yield from the basin can be calculated as the product of annual sediment yield and the values of ^{137}Cs concentration in suspended sediment depicted in Fig. 4B. A mean annual suspended sediment yield from the basin of 55 t km^{-2} year^{-1} has been assumed in the absence of a record of annual yields, and the accumulated output of ^{137}Cs for the period 1954 to the present, corrected for radioactive decay to 1985, has been estimated at 1.8 mBqcm^{-2}. this value applies to the entire basin and could be increased to 2.1 mBqcm^{-2} if it assumed that ^{137}Cs loss is minimal from

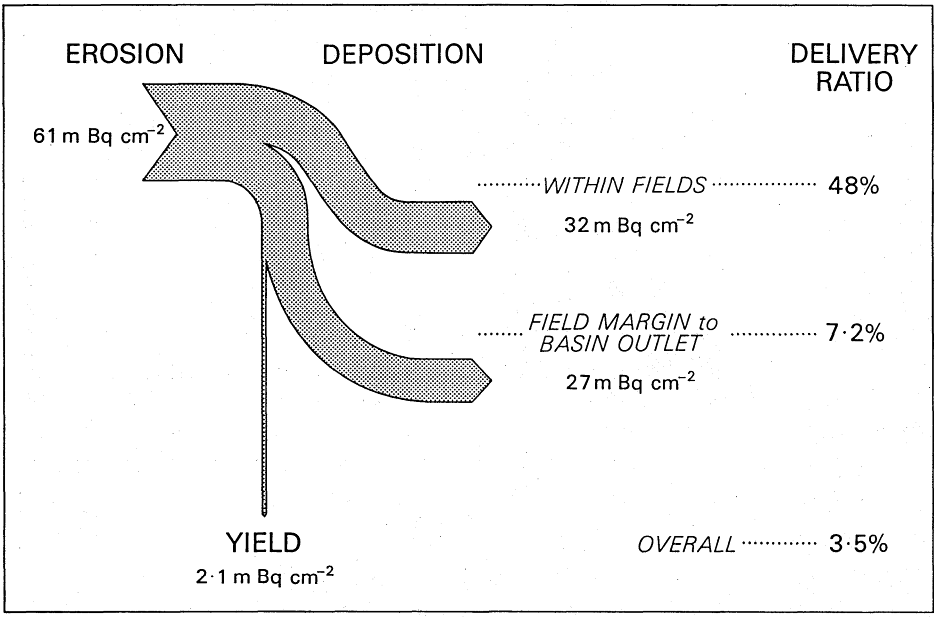


Figure 5

the undisturbed woodland and is therefore restricted to the 86 percent of the study basin which supports arable farming.

The average loss of 1.8 mBqcm^{-2} from the entire basin proposed above represents a very small proportion of the total input to the basin adjusted for radioactive decay to 1985 (i.e. 320 mBqcm^{-2}) and suggests that only approximately 0.6 percent of the total fallout has been transported from the basin. This may have important implications for the long-term fate of other radioisotopes associated with atmospheric fallout which have attracted more environmental concern (e.g. ^{90}Sr and $^{239, 240}$Pu).

If the results obtained from the detailed ^{137}Cs sampling of the four fields are taken as representative of the cultivated portion of the study basin, it is possible to produce a tentative ^{137}Cs budget for this portion of the basin. The data in Table 1 indicate that the gross rate of ^{137}Cs mobilization averaged over the entire area of the four fields is equivalent to 19 percent of the ^{137}Cs input (61 mBqcm^{-2}). Of this, 10 percent has been redeposited and 9 percent has been transported from the fields. Comparison of the gross ^{137}Cs mobilization rate (61 mBqcm^{-2}) with the output from the basin, adjusted to take account of the proportion of the basin undergoing cultivation (2.1 mBqcm^{-2}), provides an estimate of the overall delivery ratio of 3.5 percent. Similarly comparison of the amount of ^{137}Cs removed from the fields (9 percent or 29 mBqcm^{-2}) indicates that only 7.2 percent of the ^{137}Cs removed from the fields reaches the basin outlet, the remainder being deposited at the field margins and between the fields and the basin outlet. Figure 5 provides a diagrammatic representation of this tentative ^{137}Cs budget for the cultivated areas of the study basin, and emphasizes the importance of redistribution when compared to the output from the basin.

Implications for erosion rates

In the introduction to this paper it was suggested that ^{137}Cs is strongly adsorbed onto the fine fraction of the soil and that measurements of ^{137}

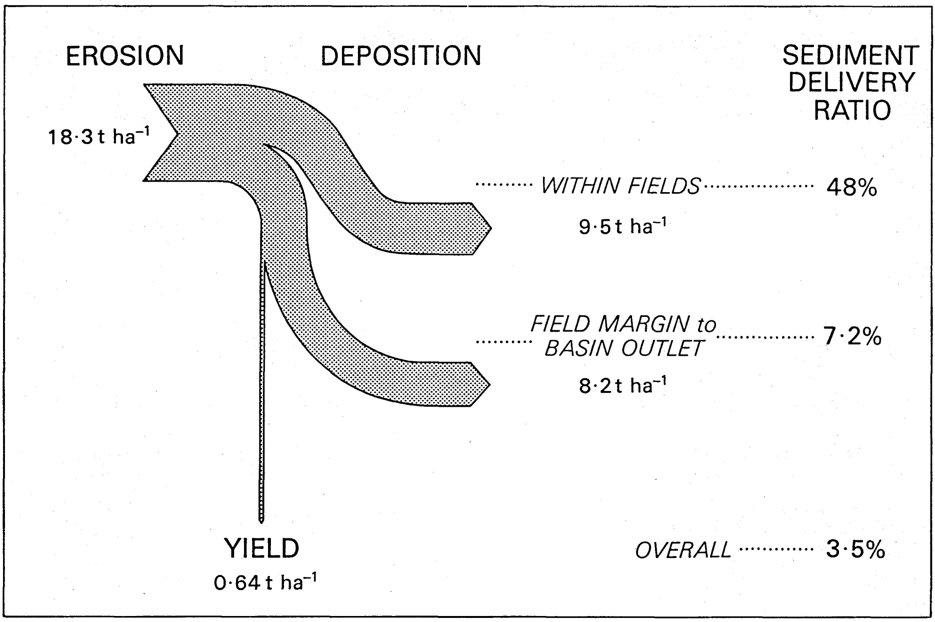


Figure 6

Cs mobilization, transport and deposition may be used to infer rates of erosion and sediment redistribution within a drainage basin. There are several possible approaches to converting values of ^{137}Cs loss and accumulation to equivalent estimates of rates of erosion and deposition (t ha^{-1}) and in this study an attempt has been made to attach such values to Fig. 5 by applying the ^{137}Cs delivery ratios calculated above. With a mean annual suspended sediment yield from the agricultural areas of the basin of 64 t km^{-2} year^{-1} and a delivery ratio of 3.5 percent, gross rates of erosion within the cultivated fields are equivalent to 18.3 t ha^{-1} year^{-1}. Taking account of deposition within the fields (52 percent of the eroded sediment) rates of soil loss from within the fields are equivalent to approximately 9 t ha^{-1} year^{-1}. Figure 6 depicts these estimates in terms of a sediment budget for the agricultural areas of the study basin.

CONCLUSIONS

Although they are limited in scope, and must therefore be seen as preliminary, it is suggested that the results presented above demonstrate that the establishment of a ^{137}Cs budget for a basin possesses considerable potential for elucidating the patterns of sediment delivery and its overall sediment budget. In the study basin, more detailed measurements are required to demonstrate the representativeness of the data obtained from the four sample fields; to test the reliability of the estimate of total ^{137}Cs output from the basin by obtaining an alternative estimate based on the overall budget of depletion and accumulation of ^{137}Cs within the basin (cf. Fig. 1); and to confirm the existence of substantial deposition of ^{137}Cs near downslope field boundaries and in other areas bordering the stream network. Furthermore additional attention needs to be given to the statistical precision of the measurements of ^{137}Cs activity (cf. Table 1) and to the standard error terms associated with the estimates of depletion, accumulation and loss.

For convenience, the values presented in Figs. 5 and 6 are depicted as absolute values, but they each possess a substantial standard error. For example the value of ^{137}Cs erosion of 61 mBqcm^{-2} depicted in Figure 5 should, more correctly, be treated as representing an estimate in the range 61-5 mBqcm^{-2} at the 95 percent level of confidence. Further investigations of the interaction between ^{137}Cs fallout and the soils of the study would also be fruitful to confirm that erosion represents the only potential mechanism for the subsequent movement of the radioisotope through the basin system.

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