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The use of caesium-137 measurements to investigate sediment delivery from cultivated areas in Devon, UK

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Abstract There is a need for empirical evidence concerning patterns of erosion and deposition on agricultural land and the proportion of the eroded sediment reaching the water courses, in order to improve our understanding and prediction of sediment delivery processes. However, such information is difficult to assemble using conventional measurement techniques. It is suggested that caesium-137 measurements offer considerable potential in this context and some results of using this approach to investigate sediment delivery from cultivated areas in Devon, UK, are presented. These measurements enable generalized maps of the spatial distribution of erosion and deposition within cultivated fields during the past 30 years to be constructed, as well as providing evidence of the proportions of the eroded soil which are redeposited within, or transported beyond, the field.

L'application des mesures au caesium-137 pour étudier la production des sédiments des terrains cultivés en Devon, RU

Résumé Il y a un besoin d'évidence empirique en ce qui concerne la distribution des pertes en sols et des dépôts dans les terrains agricoles et la proportion des pertes en sol arrivant aux cours d'eaux, pour améliorer notre compréhension des phénomènes et prédire les processus de production des sédiments. Cependant, il est difficile de rassembler cette information par les techniques de mesure classiques. Les auteurs affirment que les mesures du caesium-137 offrent un potentiel considérable dans ce contexte et ils présentent quelques résultats de l'application de cette méthode dans un étude de la productions des sédiments des terrains cultivés en Devon, RU. Ces mesures rendent possible l'établissement des cartes de distribution spatiale de pertes et de dépôts dans les champs cultivés et fournissent des estimations valables concernant les proportions du sol érodé qui sont redéposées à l'intérieur, ou transportées en dehors du champ.

INTRODUCTION

Traditionally, concern for the problem of soil erosion on agricultural land has centred on the consequent reduction in crop productivity. Against this background, efforts to develop predictive capabilities have focussed primarily on the need to estimate potential rates of on-site soil loss for a variety of crops and land management practices. Recent concern for the growing significance of sediment-associated non-point pollution from agricultural land (cf. USDA, 1976; Novotny & Chesters, 1981) and for the off-farm impacts of sediment eroded from cultivated areas (cf. Clark *et al.*, 1985) have introduced new requirements. Predictive capabilities are now required to estimate the proportion of the eroded soil that reaches the permanent water courses and therefore contributes to pollution and other downstream problems, such as reservoir siltation. The areas representing the major sources of sediment to downstream areas may not necessarily be those experiencing the maximum rates of soil loss, but they need to be identified if effective sediment control measures are to be implemented. Early attempts to estimate the fraction of the eroded soil transported downsteam from a particular area or small basin generally involved multiplying an estimate of gross soil loss, derived using an equation such as the USLE (Wischmeier & Smith, 1978), by a sediment delivery ratio. The sediment delivery ratio (SDR), defined as the ratio of sediment delivered at the basin outlet to the gross erosion occurring within the basin, provides a temporally and spatially lumped representation of the delivery efficiency of the area in question. Walling (1983) has reviewed many of the problems associated with the use of these ratios and there is undoubtedly a need to improve the representation and parameterization of the processes involved.

Advances have been made by employing a more distributed approach which considers individual fields (cf. Kling, 1974) and by a more fundamental consideration of the transport capacity of surface runoff occurring throughout the field or basin (cf. Alonso *et al.*, 1981; Dickinson *et al.*, 1986). However, progress is undoubtedly hindered by the lack of empirical data and evidence regarding actual rates of soil loss and the proportion of the eroded soil leaving individual fields, and the patterns of erosion and deposition occurring within those fields. In many instances, the only available estimates of rates of erosion and deposition and their spatial distribution are those based on the theoretical calculations being used to develop the predictive procedure. This situation is itself a reflection of the general lack of field techniques for monitoring the erosion, deposition, storage and remobilization occurring within field-sized and larger areas. Erosion plots, which have been widely used for soil erosion investigations in the past, offer little or no potential for studies of sediment delivery, in view of both their small size and the artificial boundary conditions involved.

One approach to the study of erosion and deposition within individual fields which may offer potential for providing empirical evidence of the operation of sediment delivery processes is the use of caesium-137 (^{137}Cs) as a "natural" tracer of soil and sediment movement (cf. McHenry & Ritchie, 1977; Ritchie *et al.*, 1982; Walling *et al.*, 1986; Campbell *et al.*, 1986). Caesium-137 is present in the environment primarily as a product of the atmospheric testing of nuclear devices during the late 1950s and early 1960s and fallout of this 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), although in many areas of Europe there were further significant inputs of ^{137}Cs in 1986 as a result of the Chernobyl disaster (e.g. Dorr & Munnich, 1987). Existing evidence indicates that fallout reaching the surfaces of most soils is rapidly and strongly adsorbed by the upper horizons of the soil and that further downward translocation by physico-chemical processes is limited (cf. Tamura, 1964; Frissel & Pennders, 1983). Subsequent movement of ^{137}Cs is therefore generally associated with the erosion, transport and deposition of sediment particles (e.g. Rogowski & Tamura, 1970; Campbell *et al.*, 1982). Caesium-137 has a half-life of 30.1 years and approximately 60% of the total input of this radioisotope since fallout began in 1954 could still remain within the environment. Considerable potential therefore exists for studying the movement of sediment within individual fields over the past 30 years by measuring the spatial distribution of ^{137}Cs within the soils. This contribution reports the use of ^{137}Cs measurements by the authors to document the spatial distribution of erosion and deposition and therefore the pattern of sediment delivery from agricultural fields in the vicinity of the city of Exeter in Devon, UK.

No significant input of Chernobyl fallout occurred in this location and the measurements of the ^{137}Cs content of the soils undertaken in this study relate solely to "bomb test" fallout of ^{137}Cs, most of which occurred more than 20 years ago.

THE APPROACH

The ^{137}Cs reaching the soil surface of fields in this area is rapidly and strongly adsorbed within the upper soil horizons and its subsequent movement is, in consequence, associated with the erosion, transport and deposition of sediment particles. An investigation of levels of total ^{137}Cs activity within the soil profile (mBq cm^{-2}) at different sites could provide valuable information on the spatial distribution of the effects of erosion and deposition during the past 30 years. If the measured values are compared with an estimate of the overall input, depletion would indicate erosion, whereas areas of deposition would be marked by elevated levels of ^{137}Cs. Estimates of the total or baseline input are commonly obtained by measuring the total activity at undisturbed sites located on an interfluve, where soils are unlikely to have experienced either erosion or deposition. These have been termed input sites by Campbell *et al.* (1982) and control sites by De Jong *et al.* (1983). This approach has, for example, been used by McHenry & Ritchie (1977) to study the pattern of erosion and deposition along slope transects in the White Clay Lake watershed in Wisconsin, USA, by Longmore *et al.* (1983) to map the major areas of erosion and deposition within an upland catchment on the Darling Downs, Australia, and by Loughran *et al.* (1982) to study sediment movement within a small drainage basin in the Hunter Valley, Australia.

THE STUDY AREA

The study area, which lies about 10 km north of the city of Exeter, is an area of intensive mixed farming, with the arable component dominated by cereal crops (wheat and barley) grown in rotation with ley grass, fodder beans, potatoes and swedes. It is underlain by sandstones, breccias and conglomerates of Permian age and the characteristic soils are fertile brown earths. Slopes range between about 2° and 12° and the individual fields, which are frequently bounded by hedges and banks, are typically of the order of 12 ha in size. Mean annual precipitation over the area is estimated at 800 mm, and the annual runoff is of the order of 350 mm. More than 50% of the mean annual precipitation falls between November and March, when many of the fields, which are tilled and sown with cereals in the autumn, have limited vegetation cover. The suspended sediment yields of streams in the area are typically of the order of 50 t km^{-2} and are dominated by clay- and silt-sized fractions which respectively account for about 75% and 25% of the total load.

DATA COLLECTION

Measurements of ^{137}Cs activity within the soil profile have been made using two approaches. In the first, information on the distribution of ^{137}Cs within the profile has been obtained by sampling from an area of 800 cm^2 at 2 cm increments down to 50 cm using the scraper plate technique developed by Campbell & Loughran (personal communication). This procedure is time consuming, and most measurements have involved the collection of whole core samples (42 cm^2) extending to a depth of approximately 60 cm using a purpose-built motorized percussion corer. All soil samples were subsequently air dried, disaggregated and sieved to separate the <2 mm fraction for analysis. A representative sub-sample of this fraction (*c.* 1 kg) was packed into a 1 l perspex Marinelli beaker prior to analysis. The ^{137}Cs content of the sub-samples was measured by gamma spectrometry using a Canberra Series 35 multi-channel analyzer linked to coaxial germanium detectors housed in lead shields. Count times were typically of the order of 30 000 s, providing an analytical precision (2 s.d.) of ±6%. Results were expressed in terms of the surface area of the original sample in units of mBq cm^{-2}.

RESULTS AND INTERPRETATION

Measurements of ^{137}Cs activity at a number of sites within the study area characterized by hilltop locations, minimal slopes and permanent pasture and which may therefore be equated with the "input sites" of Campbell *et al.* (1982) and the "control sites" of De Jong *et al.*. (1983), provided consistent estimates of an average baseline input of 250 mBq cm^{-2}. The representative profile for an input site depicted in Fig. 1A evidences the typical down-profile distribution of ^{137}Cs described by other workers, with most of

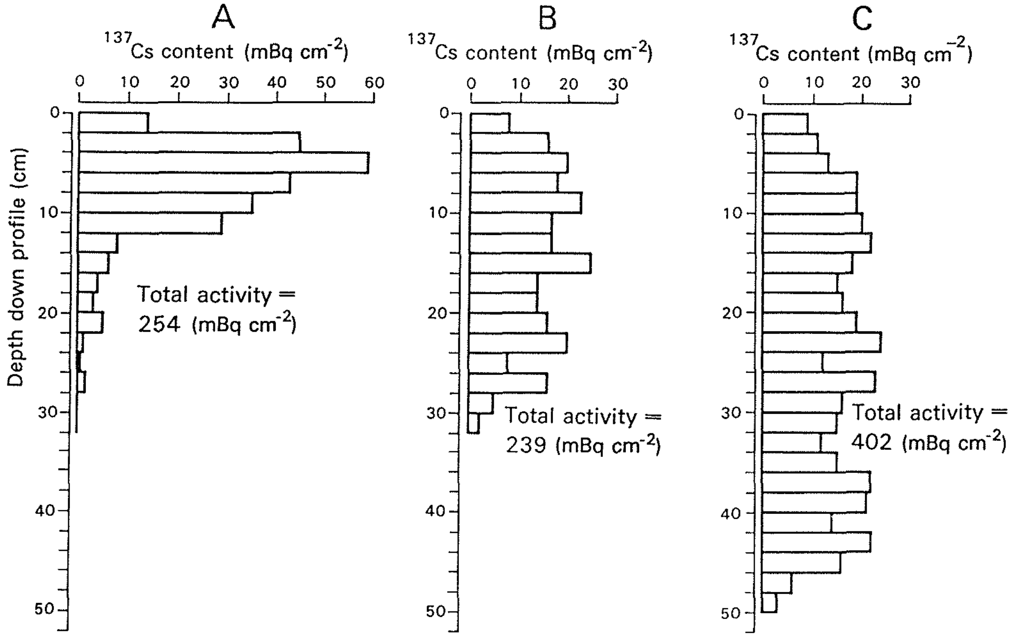

Fig. 1 Typical examples of the content and vertical distribution of ^{137}Cs in soil profiles representative of (A) undisturbed permanent pasture, (B) cultivated areas evidencing slight erosion and (C) cultivated areas evidencing deposition.

the radioisotope being contained in the top 10 cm and an exponential decrease occurring below. Profiles excavated from individual fields show clear evidence of the influence of cultivation and of erosion and deposition. The profile illustrated in Fig. 1B was obtained near the middle of a field and the almost uniform levels of ^{137}Cs recorded down to 30 cm may be ascribed to the mixing action of cultivation within the plough layer, which in this locality typically extends down to 30 cm. The total ^{137}Cs content of this profile (239 mBq cm^{-2}) is less than the input baseline of 250 mBq cm^{-2}, suggesting that some erosional loss of ^{137}Cs has occurred. The profile illustrated in Fig. 1C, which is characteristic of many located in depressions and at the foot of a slope, evidences ^{137}Cs to greater depths than the plough layer and a total ^{137}Cs content considerably in excess of the baseline input. Both features point to depositional gains of ^{137}Cs labelled sediment during a period of continuing mixing by cultivation, and are consistent with the location of this and similar sites.

Most of the data on the ^{137}Cs content of soil profiles obtained in this study relate to whole core bulk samples with a surface area of 42 cm^2. This surface area is only approximately 5% of that represented by the scraper plate profiles and attention has been given to problems of sampling variability associated with such cores. This has been investigated by collecting multiple cores from a closely spaced 3 × 3 grid at a number of sampling sites. Comparison of the results obtained for these nine replicate cores provides a means of estimating the precision of the core measurements, which in turn reflects both sampling variation and analytical variation. The values of ^{137}Cs content for the nine replicate cores collected at individual sites typically evidence a coefficient of variation of 10%, and a precision of ±20% (at approximately the 95% level of confidence) has therefore been assumed for the core data. With a typical analytical precision of ±6% (at 2 s.d.) for the core samples, sampling variability is responsible for most of the overall range of the precision ascribed to the cores. Higher coefficients of variation have been encountered for replicate samples collected from uncultivated sites under permanent pasture and this is seen to reflect the greater sampling variability associated with soils which have not been mixed by cultivation.

Micro-scale variations in porosity and permeability within such soils, particularly those associated with the distribution of macropores, could be expected to influence the initial distribution of ^{137}Cs, and, in the absence of mixing by cultivation, this will be reflected in the greater sampling variability of the small diameter core samples. In this study, values of ^{137}Cs content representative of undisturbed input sites have been based either on samples collected with the scraper plate, which involve a much larger area, or on aliquots of bulk samples comprising multiple cores.

These estimates of precision have important implications for any attempt to compare the values of ^{137}Cs obtained for cores collected from different sites and thereby to identify areas where significant erosion and deposition have occurred. Values of ^{137}Cs content for individual sites could be greater or less than the baseline reference value purely as a result of the lack of precision of the measurements, and significant differences must be distinguished from those associated with measurement and sampling variability. In this study, areas of deposition have been identified by values of total ^{137}Cs content which exceed the baseline reference value by a margin greater than the overall level of precision defined above (i.e. those sites where the ^{137}Cs content of the core samples exceeds 250 + 20% mBq cm^{-2} or >300 mBq cm^{-2}). Similarly, areas experiencing significant erosion have been identified as those areas where the ^{137}Cs content of the core sample is less than 200 mBq cm^{-2}. Areas of severe erosion have been defined as those where >40% of the total input of ^{137}Cs has been lost and a value of 120 mBq cm^{-2} (i.e. 150 mBq cm^{-2} – 20%) has been used to identify these sites.

These results of a reconnaissance survey of one field in the study area are shown in Fig. 2. With an average slope of about 12°, this field is one of the steepest under arable cultivation in the study area. Swedes and cereals have been frequent crops over the past 30 years and rilling has been observed on a number of occasions, particularly when intense summer thunderstorms have occurred shortly after the sowing of the swede crop.

More than 60 wholecore samples have been collected from this field and the values of ^{137}Cs content associated with these cores have been plotted on Fig. 2. These depict a pattern characterized by several areas of very low ^{137}Cs levels within the field, and an area of high ^{137}Cs levels along the hedge boundary at the foot of the slope. The critical values for identifying areas of deposition, erosion and severe erosion defined above have been used to produce the tentative map of erosional and depositional areas superimposed on Fig. 2. Erosion is seen to have been active over most of the field, since

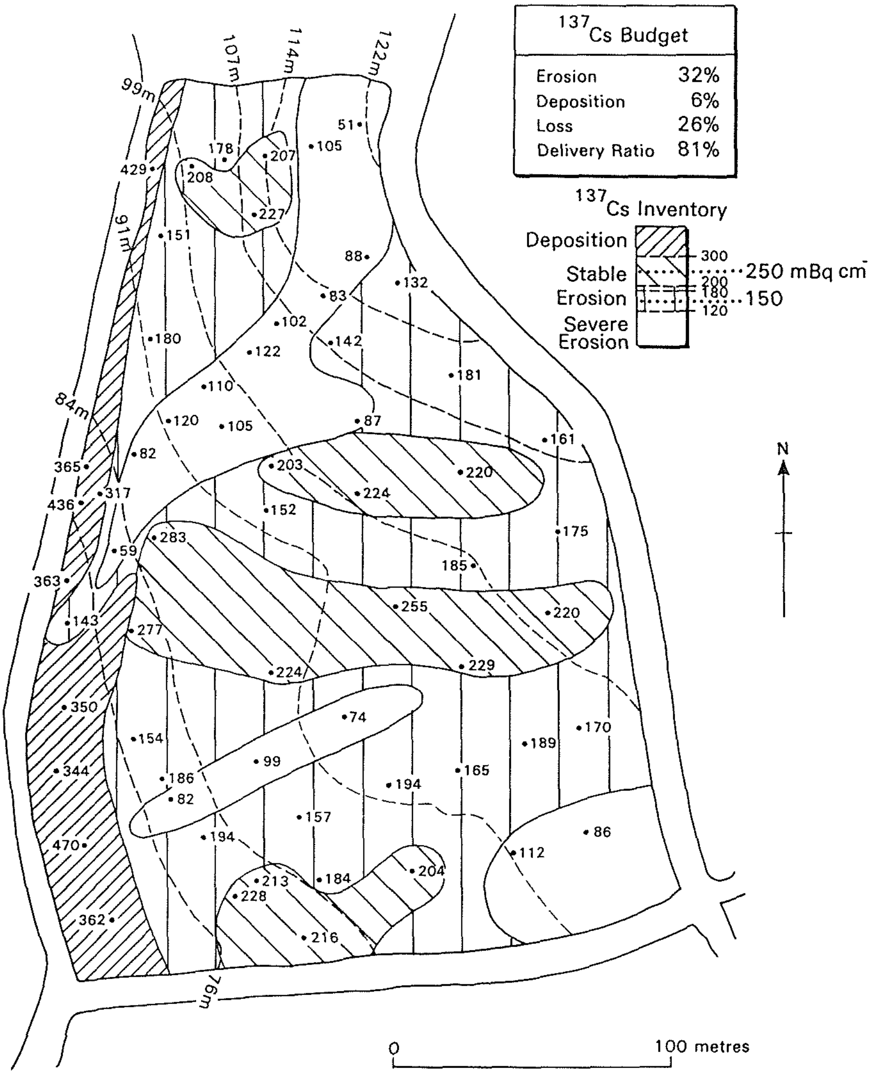

Fig. 2 The spatial distribution of ^{137}Cs content of the soil profile within a cultivated field representative of the steep portions of the study area. The mapping classes have been selected to take account of the overall level of precision of the ^{137}Cs measurements.

only relatively small areas have been mapped as stable, and there is a substantial area of severe erosion running from the top to the bottom of the slope in the northern area of the field as well as two further areas on a spur and at the top of the slope in the southern part of the field. Interestingly, the small valley-like depression which runs upslope through the centre of the field does not appear to be a focus of erosion. Rather, it is areas located on the spurs, which field observations have shown to exhibit thinner soils, that appear to experience the highest rates of erosion. These areas are the most likely to generate surface runoff during periods of heavy rainfall. A sizeable deposition zone located at the foot of the slope above the hedge boundary is also shown in Fig. 2. Comments made by the farmer indicate that the level of the field has increased significantly in this zone within living memory and this is borne out by the substantial elevation of the ^{137}Cs levels. Preliminary analysis of some samples from a profile indicate that ^{137}Cs is present in appreciable quantities to depths of *c.* 50 cm. The zone of severe erosion which runs downslope in the northern part of the field appears to breach this zone of deposition, suggesting that soil eroded from that zone was transported beyond the field rather than being deposited at the foot of the slope.

More sampling sites would be required to produce a detailed and definitive representation of the pattern of erosion, deposition and sediment delivery within this field, but some preliminary conclusions may be advanced. These include the observation that all the material mobilized by erosion in the area of the field upslope of the zone of deposition bordering the hedge boundary appears to be transported either into or beyond the deposition zone. There is no evidence of deposition higher up the slope. This is consistent with the observations of rill development noted above. There is also evidence that the zones of maximum erosion are to be found in spur locations where the soils are thinnest. Further analysis of the levels of ^{137}Cs plotted at the individual sampling sites has been undertaken to estimate the proportion of the overall input of ^{137}Cs that has been mobilized by erosion, the proportion that is currently stored in the depositional zone, and the proportion that has been transported beyond the field. In order to undertake these calculations it has been assumed that the sample points provide a representative sample of the conditions in the field and that the analytical and sampling variability discussed previously is essentially random. The absolute values can then be compared directly with the baseline reference value of 250 mBq cm^{-2}. The amount of ^{137}Cs currently stored in the depositional zone has been estimated as the product of the area of this zone and the mean ^{137}Cs level for the sites within it. The results are presented as a "^{137}Cs budget" in Fig. 2. They confirm that most of the ^{137}Cs mobilized by erosion has been transported beyond the field and the sediment delivery ratio, which expresses this value of loss as a proportion of the total erosion, is as high as 81%.

Figure 3 provides another example of a survey of ^{137}Cs levels in the soils of a cultivated area. In this case several contiguous fields are involved, and they have been selected to be representative of an area with much lower slope angles than those encountered in Fig. 2. Here, the average slope angle is approximately 3°. The same procedure has been employed to map the pattern of erosion and deposition, except that no areas of severe erosion are present, and this has been superimposed on Fig. 3. Several contrasts with the pattern shown on Fig. 2 are immediately apparent. Firstly, there are substantial areas classified as stable and which therefore have experienced negligible or only very low rates of erosion. Secondly, as noted above, there are no areas classified as indicating severe erosion and both this and the previous contrast indicate that erosion rates are lower in this area of gentler

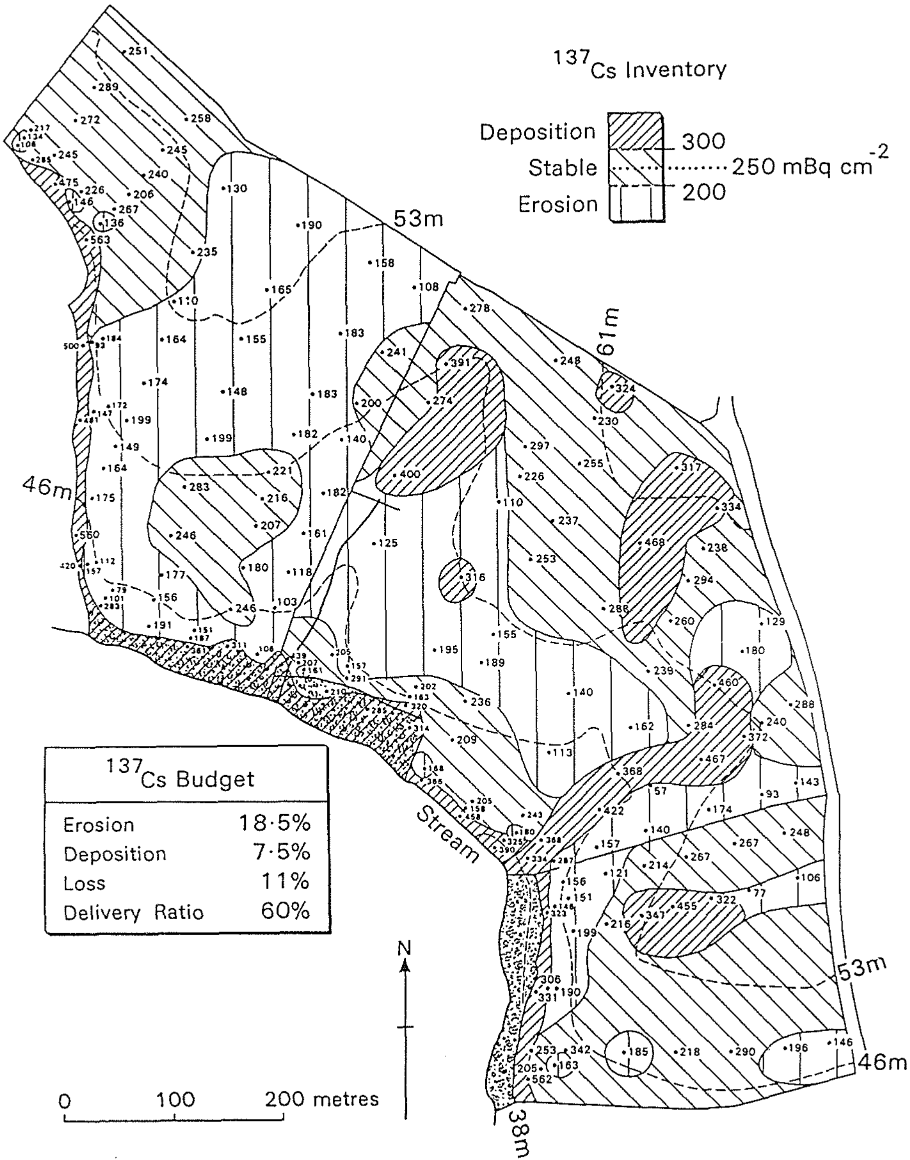

Fig. 3 The spatial distribution of the ^{137}Cs content of the soil profile within a group of cultivated fields representative of the portions of the study area with more subdued topography. The mapping classes have been selected to take account of the overall level of precision of the ^{137}Cs measurements.

slopes. Thirdly, in this area there is evidence of deposition ***within*** the field, as well as along the downslope field boundary. This indicates that some of the eroded soil has been redeposited before reaching the boundary of the field and that a less efficient delivery system is therefore involved. Most of this within-field deposition is located in topographic depressions associated with the two small valley-like features which dissect the area. Comparison of the

^{137}Cs levels associated with the within-field depositional areas with those found in the depositional zone along the downslope field boundary, indicates that the latter generally exhibits greater amounts of deposition. However, there is a tendency for amounts of deposition to be lower in those portions of this boundary zone lying downslope of areas of within-field deposition than in those portions with no areas of deposition upslope. Again, however, the higher rates of erosion appear to be preferentially located on the spur areas. The ^{137}Cs budget for these fields, which has been estimated in the same way as that presented for Fig. 2, embodies many of the contrasts noted above. The overall proportion of the ^{137}Cs input that has been mobilized by erosion is little more than half of that mobilized in the steeper field represented by Fig. 2. In addition, more of the eroded ^{137}Cs has been deposited within the field or along the field boundary and in consequence, the overall delivery ratio is significantly lower. This lower delivery ratio may reflect both the lower slope angles and the lack of any evidence of significant rill erosion.

PERSPECTIVE

The results presented above provide a useful assessment of the pattern of erosion and sediment delivery from cultivated fields in the study area during the past 30 years. It must be recognized that the findings relate to the mobilization and transport of ^{137}Cs rather than the soil itself, but there would seem little doubt that the two are intimately connected and that ^{137}Cs measurements can be used with advantage to trace sediment movement in environments such as the study area. Two aspects, however, merit further research if the full potential of this approach is to be realized. Firstly, more information on the particle-size selectivity of ^{137}Cs adsorption is required, since the pattern of ^{137}Cs levels will reflect the mobilization, transport and deposition of those fractions with which the radioisotope is associated, rather than that of the overall soil. It is, for example, possible that the delivery ratios cited in Figs 2 and 3 overestimate the true sediment delivery ratios, since mobilization and subsequent deposition of coarse particles would not be reflected by the ^{137}Cs measurements if the radioisotope is preferentially associated with the fine fraction. Secondly, the information presented here provides no indication of the actual rates of erosion operating in the fields. A number of workers have attempted to produce empirical and theoretical relationships between the percentage loss of ^{137}Cs from a soil profile and the rate of soil erosion (cf. Kachanoski & De Jong, 1984; Kachanoski, 1987; Campbell *et al.*, 1986) but further work is required to test their accuracy and transferability and to explore alternative means of establishing such relationships.

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