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Estimating erosion using caesium-137: I. Measuring caesium-137 activity in a soil

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Abstract Mean areal activities of ^{137}Cs under forest, grazing and cultivated land use were estimated. Activities under each land use were significantly different; the forest site had the greatest ^{137}Cs activity and the cultivated sites had the least. Variability in ^{137}Cs activity at each site was high and was primarily dependent on land use. The coefficient of variation ranged from 21% for a 0.4 ha cultivated site to 45% for the 0.02 ha grazing site. Variability was attributed to (a) an initially nonuniform distribution of ^{137}Cs within the soil, (b) small scale redistribution of topsoil controlled by micro topography and not resulting in a net export of soil and (c) erosion. Estimates of the number of samples required to estimate a mean activity with a standard error of less than 5% ranged from 19 for the cultivated sites to over 80 for the grazing site. The large number of samples required to accurately estimate a mean activity makes the routine application of this technique impracticable. A method for estimating activity by bulk sampling is suggested for these applications.

Estimation de l'érosion par l'emploi de caesium-137: I. Mesure de l'activité du caesium-137 dans un sol

Résumé On a évalué le degré d'érosion sur un terrain couvert de forêts, de pâturage et de cultures. Les activités pour chaque type de couverture du sol étaient très différentes. On a trouvé le plus grand degré d'activité (^{137}Cs) sous la forêt et le plus faible en terrain cultivé. Les variations de ^{137}Cs en activité d'un type de couverture à un autre étaient très grandes et dépendaient tout d'abord de l'utilisation des sols. Le pourcentage variait de 21% pour une superficie de 0.4 ha de terrain cultivé à 45% pour une superficie de 0.02 ha de pâturage. Ces variations ont été attribuées à: (a) un distribution inégale au départ de ^{137}Cs au sein du terrain; (b) la redistribution à petite échelle d'une couche de terre arable controlée par une micro topographie et ne résultant pas d'un transport majeur de terrain; (c) l'érosion. Les estimations du

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nombre d'échantillons nécessaires pour évaluer l'activité moyenne avec une marge d'erreur de 5%, variaient de 19 pour les terrains cultivés à plus de 80 pour les pâturages. Le nombre important d'échantillons nécessaire pour évaluer avec précision une activité moyenne rend l'application de cette technique difficile. Il est suggéré, pour ce travail, une méthode utilisant un échantillonnage global.

INTRODUCTION

Most estimates of topsoil erosion in sediment budgets rely on the use of the Universal Soil Loss Equation. The application of this empirically derived equation beyond the data base from which it was derived will always be open to question. The measurement of the retention of the fallout isotope ^{137}Cs has the potential to provide a universal physically based method of estimating soil loss. Little information is available concerning sampling designs for estimating ^{137}Cs activity in the soil or on methods of estimating soil loss from these data.

Part I of this paper describes attempts to measure the areal activity of ^{137}Cs at two forest sites and adjacent eroded sites. The spatial variability at each site is reported as well as estimates of the number of samples that are required to estimate mean ^{137}Cs activity at each site so that the standard error of the mean is less than 5%. Three methods of estimating soil loss from ^{137}Cs activity in the soil are described in Part II and the results from each method are compared.

STUDY SITES

The study sites are situated at Inverell and North Star in northern New South Wales, Australia. At Inverell the topography is mainly flat with slopes generally less than 3°. The land has been extensively cleared for cultivation. Sheet erosion and even gully erosion has become a problem in the area because of the coincidence of cultivation with high intensity summer rainfall (Anon, 1972).

At North Star the slopes are generally less than 5%. The land has been extensively cleared for grazing and in recent years there has been an increase in cropping in the district. This has resulted in substantially increased soil erosion in the area (Hart & Armstrong, 1983).

Six sites were sampled in all. One forest site, one pasture site and two cultivated sites were located near Inverell. One forest site and one cultivated site were located near North Star. The cultivated sites near Inverell have been cropped annually since 1954. The North Star site was used for grazing until 1974 when it was cleared for annual cultivation.

SAMPLING METHODS AND LABORATORY ANALYSIS

Two soil sampling procedures were used; detailed sampling using a 2 cm vertical sampling interval and coarse sampling using a 15 cm vertical sampling interval. Sample sites were excavated to a depth of 30 cm where soil depth permitted, in order to recover the bulk of the ^{137}Cs present in the soil. Samples were oven dried at 110°C and passed through a 2 mm sieve. Caesium-137 activity was determined by gamma-spectrometry using a Ge detector. Total activity was expressed as an areal concentration (Bq m^{-2}) corrected to 1985.

RESULTS AND DISCUSSION

Mean areal activity of ^{137}Cs, standard error of the mean (S_E) and the coefficient of variation (*CV*) for each site are given in Table 1. Caesium-137 activity is highest in the forest sites and lowest in the cultivated sites. The pasture site at Inverell had a 17% reduction in ^{137}Cs activity in comparison to the near-by forest site while the cultivated sites showed 55% and 59% reductions in activity. In comparison the North Star cultivated site had only a 34% reduction in activity in comparison to the adjacent forest site.

Table 1 *Coefficients of variation for each sample site*

Site	*Mean activity (Bq m^{-2})*	*N*	S_E	*CV*	*Reduction in activity*	*Area (ha)*
Inverell						
Forest site	*1451*	*11*	*147*	*34%*	-	*1*
Pasture site	*1211*	*7*	*205*	*45%*	*17 ± 17%*	*0.02*
Cultivated site A	*654*	*13*	*40*	*21%*	*55 ± 10%*	*0.4*
Cultivated site B	*588*	*8*	*58*	*28%*	*59 ± 11%*	*0.02*
North Star						
Forest site	*798*	*15*	*68*	*33%*	-	*0.02*
Cultivated site	*527*	*15*	*34*	*25%*	*34 ± 10%*	*0.02*

The ^{137}Cs activity at the cultivated and pasture sites closely reflects the known erosional history. The pasture site at Inverell is located within a Travelling Stock Route and has probably maintained a good cover of vegetation and undergone considerably less soil loss than the cultivated sites since 1954. Both cultivated sites show very large reductions in ^{137}Cs activity. These sites are dissected by shallow gullies and are known to have undergone severe erosion. The North Star site shows proportionally less reduction in activity than the Inverell sites, a fact that is consistent with its shorter history of cultivation.

This investigation has shown that there is a large degree of spatial variability in the distribution of ^{137}Cs in the soil. All sites had *CV*s in excess of 20% and the pasture site has a *CV* in excess of 40%. This level of variability in ^{137}Cs activity is not unexpected, soil properties are notoriously variable and *CV*s much less than those reported here would be the exception rather than the rule (cf. Beckett & Webster, 1971).

Variability appears to be primarily related to land use. The pasture site has the highest level of variability with a *CV* of 45%. The forest sites the next highest levels of variability with *CV*s of 34% and 33%. The cultivated sites at Inverell and North Star showed the lowest levels of variability with *CV*s between 21% and 28%.

There are a number of factors and processes which are likely to be responsible for the variability found in these soils:

(a) **Non-uniform deposition of ^{137}Cs** The initial assumption of uniform deposition of ^{137}Cs onto the soil and redistribution within the soil is not necessarily valid. Caesium-137 is removed from the atmosphere by rainfall and is subsequently immobilized in the soil by the strong binding of this cation to clay particles and organic matter (Tamura, 1964; Lomenick &Tamura, 1965; Ritchie *et al.*, 1970). However, although sorption of caesium to these soil particles is very strong, immobilization does not occur instantaneously. Consequently, the distribution of ^{137}Cs in the soil is likely to be controlled to some extent by the distribution of infiltrating rainwater. This can be substantially affected by the interception of rainfall by vegetation and by the presence of macropores and desiccation cracks in the soil. Lance *et al.* (1986) reported that the spatial variability in infiltration rates measured at their sites was compatible with the variability they found in ^{137}Cs activity.

(b) **Redistribution of enriched topsoil** Once sorption of ^{137}Cs to the clay particles and organic matter in the soil has occurred there may subsequently be small scale redistribution of soil without any net export from an area. Rainsplash and rainwash (Moss *et al.*, 1979; Moss & Green, 1983) may relocate topsoil (especially the finer fraction with very high concentrations of ^{137}Cs) under the local influence of microtopography. Rogowski & Tamura (1970) believed these processes were primarily responsible for the highly variable distribution of ^{137}Cs (*CV* = 110%) they found within their small (2.3 m × 2.3 m) bare soil plot. Redistribution of topsoil around the tussocky grass cover at the pasture site may also be responsible for the very high variability at this site.

(c) **Channelized erosion** If rainfall and soil conditions are suitable, intense rainfall can result in the occurrence of channeled overland flow. This results in spatially concentrated loss of soil from an area by rilling which may substantially increase variability. The effects of rilling are not thought to be significant at the highly eroded cultivated sites at Inverell because of the effects of frequent cultivation. Rilling may be a significant cause of variability at sites where cultivation is less severe (cf. Lance *et al.*, 1986).

(d) **Cultivation** In contrast to the results of Lance *et al.* (1986) and Rogowski & Tamura (1970) this study found that the lowest levels of variability occurred in the most eroded cultivated sites. Regular cultivation may have two effects on the distribution of ^{137}Cs in the soil. Cultivation could homogenize the soil contained within the plough layer resulting in less variability in ^{137}Cs activity. It could also evenly distribute the effects of soil loss by rilling which will in turn tend to reduce the spatial variability in ^{137}Cs activity.

Given that there is a significant degree of variability in the activity of ^{137}Cs in the soil, how many samples are required to achieve an acceptable uncertainty in the determination of the mean activity of ^{137}Cs in the soil? The answer to this depends primarily on the definition of acceptable uncertainty. The number of samples required at each site can then be estimated (approximately) using the relationship

$$N = \left[\frac{CV}{X}\right]^2 + 1$$

where CV is the estimated coefficient of variation for the parameter and X is the desired standard error of the mean (S_E) expressed as a percentage of the mean. The number of samples required at each site so that SE of the mean is less than 5% and 10% are given in Table 2. It can be seen from this table that the level of accuracy required in the determination of the mean has a great affect on sampling requirements. The required number of samples varies from 19 for the cultivated sites to over 80 for the pasture site for S_E less than 5% but only 7 to 21 samples are required for a S_E less than 10%.

Table 2 Number of sample (N) required to estimate mean activity so that the standard error (S_E) is less than 5% and 10% of the mean

Site	*N(S_E < 5%)*	*N (S_E <10%)*
Inverell		
Forest site	*46*	*12*
Pasture site	*82*	*21*
Cultivated site A	*19*	*6*
Cultivated site B	*32*	*9*
North Star		
Forest site	*45*	*12*
Cultivated site	*26*	*7*

Given the amount of counting time required to measure ^{137}Cs activity in the soil (8 to 16 hours for each sample) the number of samples required can easily become unmanageable for routine analysis. It is suggested that the best strategy for estimating mean ^{137}Cs activity at a large number of sites is to make a preliminary investigation to assess variability for each land use or land form. The number of samples required for accurate assessment of a mean activity can then be estimated for each site. Once collected these samples can be bulked together for a single analysis of ^{137}Cs activity.

The question remains as to the size of the area that should be sampled when estimating ^{137}Cs activities. The answer to a great extent will depend on the nature of each investigation, the land use and the time and analytical facilities available. The limited data reported in the literature imply that variability in ^{137}Cs activity is high over relatively small distances and increases with increasing sampling area.

An indication of the role of scale on variability can be obtained by considering data reported from a single land use. This study found *CV*s ranging from to 22% to 28% over 0.02 to 0.4 ha in cultivated soils. Data from Loughran *et al.* (1987) showed *CV*s of 29%, 35% and 40% for cultivated fields of approximately 3.6, 5.4 and 6 ha respectively, data from Longmore *et al.* (1983) showed a *CV* of 49% over a sampling area of approximately 32 ha. In the only detailed study of ^{137}Cs variability published in the literature Lance *et al.* (1986) found that variability between samples 1 m apart (*CV* = 14%) was less than the variability between samples at 10 m spacing (*CV* = 30%) but that there was no structure in the spatial variability.

These rough estimations of spatial variability are in general agreement with the results of Beckett & Webster (1971) who found that for many soil properties as much as half the *CV* present within 1 ha is already present within a few square metres. This has serious implications for attempts to map the distribution of soil loss in the landscape. Mapping ^{137}Cs distribution in the landscape with single samples will only be possible if the samples are very closely spaced and if the variation in ^{137}Cs activity caused by soil loss is much greater than variation caused by other processes.

Sampling larger areas encounters the problem of increasing spatial variability, probably a result of differential soil losses in the broader landscape. An accurate estimate of the mean can still be made if a sufficiently large number of samples are collected but the investigator is still left with the decision of how much variability is acceptable within a sampling unit.

CONCLUSIONS

This study served as a preliminary investigation of the amount and variability of ^{137}Cs in the soil under three different land uses. Caesium-137 activity is substantially different at each site and reflects the erosion status of each site. Variability is not unusually high for a soil property, but the degree of variability found presents serious sampling problems because of the long counting times involved in ^{137}Cs analyses. Variability appears to be primarily dependent on land use and sampling area.

The variability in ^{137}Cs activity in the soil precludes the use of individual samples for soil loss estimates. The high spatial variability also suggests that interpolation of activity between sites will be uncertain unless they are very closely spaced. The routine analysis of large numbers of samples in erosion surveys is likely to be impractical. It is suggested that once an estimate of variability has been made then any further samples collected be bulked for analysis.

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