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Estimating erosion using caesium-137: II. Estimating rates of soil loss

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Abstract Three methods are available for converting a measurement of ^{137}Cs depletion in a soil to an estimate of soil loss: (a) a simple linear relationship between the two variables; (b) empirically derived relationships between the reduction in ^{137}Cs activity and soil loss; and (c) mass balance models. Each of these techniques was used to estimate rates of soil loss from a site at Inverell, Australia. Using a linear relationship soil loss was calculated to be 106 t ha^{-1} year^{-1}. Estimates of soil loss using a mass balance model were found to be greatly affected by the assumptions used in the model and the temporal distribution of soil loss events used in the model (25–80 t ha^{-1} year^{-1}). The empirically derived relationship was found to yield estimates an order of magnitude lower (1.5 t ha^{-1} year^{-1}). Each method needs to be calibrated using erosion plot data for a wide variety of soils and landuses before any confidence can be placed in estimates of soil loss.

Estimation de l'érosion par l'emploi de caesium-137: II. Estimation du taux de pertes en sol

Résumé Il existe trois méthodes pour convertir les degrés de réduction d'activité du ^{137}Cs dans le sol en taux d'érosion: (a) une relation linéaire basée sur la concentration de ^{137}Cs du moment dans la couche de terre arable; (b) des relations empiriques entre la réduction d'activité en ^{137}Cs et l'érosion; (c) des modèles du bilan des masses. Chacune de ces techniques a été utilisée pour évaluer le taux d'érosion sur le site de Inverell en Australie. Avec l'emploi de la relation linéaire, le résultat des calculs du taux d'érosion a été de 106 t ha^{-1} an^{-1}. On a constaté que les évaluations de degré d'érosion calculées avec des modèles du bilan de masse, étaient énormement affectées par les hypothèses émises pour la mise au point du modèle et la distribution temporelle d'évènements érosifs utilisée dans le modèle (25–80 t ha^{-1} an^{-1}). On a constaté que les relations empiriques donnaient aux évaluations un ordre de grandeur plus bas par les autres méthodes (1.5 t ha^{-1} an^{-1}). Chaque

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méthode doit être étalonnée en utilisant les informations sur l'érosion sur parcelles pour une grande varieté de sols et de leurs utilisations — avant que l'on puisse faire confiance à ces estimations d'érosion.

INTRODUCTION

There are three methods for quantitatively estimating rates of soil loss from ^{137}Cs activity in a soil:

(a) by assuming soil loss is directly proportional to the amount of ^{137}Cs removed from the soil;

(b) using a mass balance model of ^{137}Cs accumulation from fallout and removal by soil erosion (see Kachanoski & De Jong, 1984).

(c) using an empirical relationship between soil loss and ^{137}Cs depletion (Ritchie *et al.*, 1974; Campbell *et al.*, 1986a,b).

This study investigates rates of soil loss estimated using each of these three methods for the cultivated site A at Inverell, which has undergone a 55% ± 10% reduction in ^{137}Cs relative to a near-by uneroded forest site (see Part I). These results are then compared to an estimate of the rate of soil loss made using the USLE.

ESTIMATION OF SOIL LOSS USING A LINEAR RELATIONSHIP

The amount of soil loss from a site can be estimated using a linear relationship of the form

$$S = (C/K * W_p)/Y$$

where:

S = soil loss in t ha^{-1} $year^{-1}$;
C = relative depletion in ^{137}Cs activity (%);
K = areal concentration of ^{137}Cs per millimetre of soil (% of total fallout mm^{-1};
W_p = mass of each millimetre depth of soil (t ha^{-1});
Y = number of years since 1954.

This method requires that an estimate be made of the average concentration of ^{137}Cs in the soil for the period since 1954. This was calculated to be approximately 0.21% per millimetre of soil for the cultivated site (assuming an even distribution of fallout through the plough layer each year). This results in a soil loss estimate of 106 ± 20 t ha^{-1} $year^{-1}$.

ESTIMATION OF SOIL LOSS RATES USING A MASS BALANCE MODEL

A mass balance model of ^{137}Cs accumulation in the soil was developed to estimate rates of soil erosion using ^{137}Cs depletion data and a variety of meteorological data. The model is an adaptation of the model developed by Kachanoski & De Jong (1984) to estimate rates of soil loss that occurred in the time interval between two measurements of ^{137}Cs activity. The model was adapted to use an initial zero activity in the soil in 1954 and was run using a one year time step. The areal activity of ^{137}Cs in the soil at the end of each year is given by

$$A_t = A_{t-1} + D_t - K_1 E_t Ap_t - K_2 A_t$$

where:

t = time (years);
A_t = total ^{137}Cs in plough layer (Bq ha^{-1});
D_t = atmospheric deposition of ^{137}Cs (Bq ha^{-1});
E_t = soil loss (t ha^{-1});
Ap_t = concentration of ^{137}Cs in the plough layer (Bq t^{-1});
K_1 = enrichment coefficient of ^{137}Cs in eroded soil material;
K_2 = radioactive decay constant for ^{137}Cs (0.023 $year^{-1}$).

This is a mass balance equation for ^{137}Cs in the soil and treats the accumulation and loss of ^{137}Cs as a simple time dependent step process. A one year time step was used in this case but finer subdivision could be used.

The time pattern of fallout from 1954 to the present was assumed to be the same as that estimated for Brisbane by Longmore *et al.* (1983) and the total amount of fallout for the site was estimated as being equal to the ^{137}Cs activity found within the soil of the forest site.

Eight per cent of each year's fallout is added to the subsoil store where it is unavailable to soil erosion processes. This results in the 120–300 mm depth interval of the soil model having a ^{137}Cs activity approximately equal to the measured activity, the remainder is retained and uniformly mixed within the plough layer (upper 120 mm of soil) by annual cultivation.

Preferential removal of ^{137}Cs from the soil occurs during soil erosion because of the association of ^{137}Cs with fine soil particles and organic matter. The model uses the same "enrichment" factor (K_1 = 1.1) as used by Kachanoski & De Jong (1984).

The most significant unknown factors in the model are the time pattern of soil loss and the movement and mixing of ^{137}Cs in the soil. Soil loss predictions using three different estimates of the temporal pattern of erosion and three different ^{137}Cs infiltration rates were used to assess the sensitivity of the model to these parameters. Initially it was assumed that yearly fallout was uniformly mixed throughout the plough layer while the temporal patterns of soil loss were varied.

1. Constant rate of annual soil loss

This is the crudest estimate of the temporal distribution of soil loss and is unlikely to hold completely true for the Inverell region. For a 55% reduction in ^{137}Cs activity the model predicts a mean rate of soil loss of 60 ± 10 t ha^{-1} $year^{-1}$ since 1954.

2. **Annual soil loss proportional to the product of rainfall erosivity and a crop cover factor**

Estimates of the temporal distribution of soil loss can be made using the product of the rainfall erosivity (monthly EI-30) and crop cover (*C*) factors from the USLE. The soil erodibility, slope/length and management factors of the USLE can be ignored in this case because they have been constant for this site since 1954.

The time distribution of soil loss estimated using these two factors and the accumulation of ^{137}Cs in the soil are shown in Fig. 1. It can be seen that there is a relatively even distribution of the EI-30.*C* factor for the period under consideration with a very small concentration of erosion events in the 1950s. This results in the model estimating a mean rate of soil loss of 65 ± 10 t ha^{-1} year^{-1}.

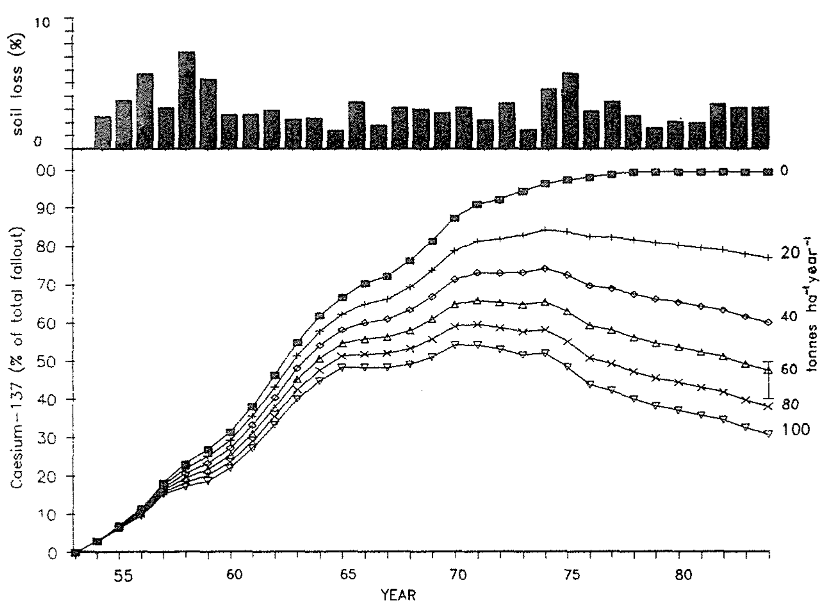

Fig. 1 Accumulation of ^{137}Cs in the soil predicted by a mass balance model. The distribution of erosion events is estimated from annual values of an EI-30.C index and is expressed as a percentage of total soil loss.

3. **Erosion events as discrete catastrophic events**

Using data from three Soil Conservation Research Stations in New South Wales, Edwards (1980) found that in a 26 year period 72% of erosion was caused by only four runoff events. These infrequent catastrophic events occur because of unfavourable coincidences of factors such as high antecedent rainfall, recently cultivated soil and low weed cover with prolonged high intensity rainfall. These factors are known to be highly variable and cannot easily be predicted in deterministic models.

The method used in this paper is to restrict soil loss to those events that exceed an arbitrary EI-30.*C* value. This limits soil loss to events that have a coincidence of high rainfall intensity and a high crop cover factor (bare soil). Investigations with the model showed that the use of a cut off value for EI-30.*C* of 30 resulted in a maximum estimate of soil loss of 80 ± 10 t ha^{-1} $year^{-1}$ (Fig. 2) as a result of a concentration of erosion events in the 1950s. The use of higher cut off values resulted in a more even temporal distribution of soil loss as a result of the occurrence of two similarly sized very large events in 1958 and 1976.

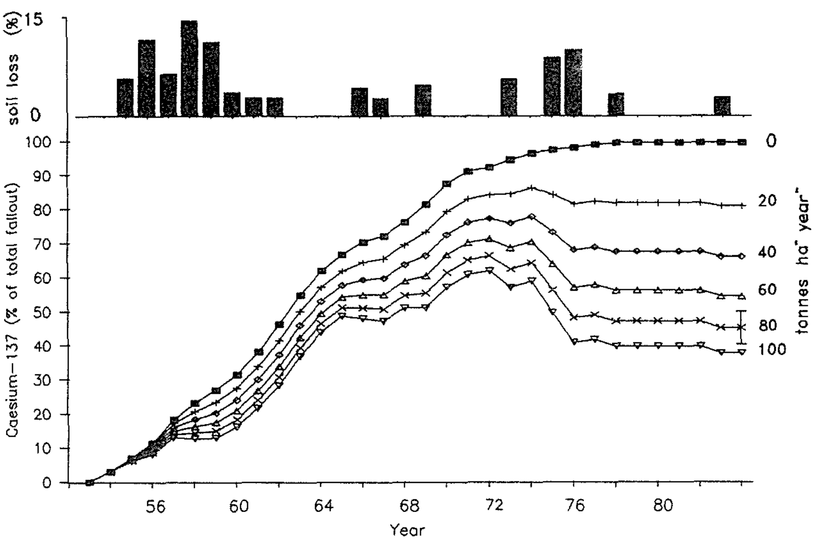

Fig. 2 Accumulation of ^{137}*Cs in the soil predicted by a mass balance model. Soil loss events are proportional to EI-30.C for values greater than 30. This cut off value yields the highest estimate of soil loss for this site.*

4. Non-uniform distribution of ^{137}Cs in the plough layer

The model has so far assumed that annual tillage evenly distributes ^{137}Cs throughout the plough layer each year — a situation that is most unlikely to be true. The concentration of ^{137}Cs in the top few centimetres of the soil is likely to remain high each year, despite the mixing effect of annual tillage. If each year's fallout was retained in the top few millimetres of soil before mixing, then the soil removed by erosion would come from a shallow layer enriched in ^{137}Cs.

Retaining the current year's fallout in the top 10 mm resulted in soil loss estimates of 37–45 t ha^{-1} $year^{-1}$ (depending on the temporal pattern of erosion) compared to the 60–80 t ha^{-1} $year^{-1}$ calculated above with a uniform distribution of fallout through the plough layer. Retaining each year's fallout in the top 5 mm reduced soil loss estimates to 25–31 t ha^{-1} $year^{-1}$. Use of retention layers thinner than this will continue to reduce estimated rates of soil loss but they are not thought to be physically justified.

ESTIMATION OF SOIL LOSS USING EMPIRICAL RELATIONSHIPS

Two empirical relationships have been developed that relate rates of soil loss to depletion of ^{137}Cs in the soil (Ritchie *et al.*, 1974; Campbell *et al.*, 1986a,b). Of these two relationships the one developed by Campbell and others is the most applicable to this study as it was developed in the Southern Hemisphere where atmospheric fallout was considerably lower than in the Northern Hemisphere. This relationship also has the advantage of having been developed on Australian soils which contrast markedly to many soils found in North America.

The relationship developed by Campbell *et al.* (1986b) is

$$S = 4.54C^{1.45} \text{ for } C < 60\%$$

$$S = 0.04C^{2.74} \text{ for } C > 60\%$$

where S = soil loss (kg ha^{-1} $year^{-1}$); C = relative depletion in ^{137}Cs activity (%).

Using the relationship a 55% reduction in ^{137}Cs activity corresponds to an average annual erosion rate of 1516 kg ha^{-1} $year^{-1}$ or 1.5 t ha^{-1} $year^{-1}$. The uncertainty associated with soil loss estimates using empirical relationships is hard to assess without published data on confidence limits. The spread of the data and the uncertainty associated with estimates of ^{137}Cs activity indicated that rates of soil loss could lie between about 0.4 and 10 t ha^{-1} $year^{-1}$.

DISCUSSION

The results of the present experiment do not permit us to state which is the most accurate method of estimating soil loss. It does permit us to note that there are very large variations and very large uncertainties in the estimates produced by each method.

Because of the simplifications inherent in the linear soil loss model this method is likely to be the least accurate. Estimates of soil loss will be determined to a great extent by the concentration of ^{137}Cs per unit mass of soil that is assumed in the model. This method has the advantage of simplicity, it requires no additional data and can be used in any investigation to give a first order estimate of soil loss once the calibration has been improved.

The mass balance model attempts to overcome many of the simplifications of the linear model. Estimates of the temporal distribution of erosion events and the vertical distribution of ^{137}Cs in the soil profile are problematical. The validity of assuming a constant annual rate of soil loss or that annual soil loss is proportional to an annual EI-30.*C* factor is questionable in the light of the limited data available on the distribution of soil loss events under Australian conditions (Edwards, 1980, 1985). Estimates of soil loss could be changed by up to 20 t ha^{-1} year^{-1} by changing the distribution of soil loss events.

The model was found to be even more sensitive to assumptions concerning the distribution of ^{137}Cs in the soil — estimates of soil loss can be halved by changing the depth of initial penetration. Little information is available concerning the penetration of ^{137}Cs in the soil over very short time periods, consequently no experimentally derived values could be used in the model at this stage.

Estimates of soil loss using the mass balance model and linear relationships both resulted in very high estimates of soil loss when compared to USLE estimates for the site (24 t ha^{-1} year^{-1}). Other workers have also reported very high estimates of soil loss. Kachanoski & De Jong (1984) estimated rates of soil loss up to 191 t ha^{-1} year^{-1} for cultivated sites in Saskatchewan. Pennock & De Jong (1987) while predicting soil losses between 10 and 17 t ha^{-1} year^{-1} found that these estimates were 2–9 times higher than soil loss predicted by the USLE. While it is possible the USLE may underestimate soil loss, the large number of uncertainties involved in using ^{137}Cs to estimate soil loss cannot be ignored. Both the linear model and the mass balance model are very sensitive to the distribution of ^{137}Cs in the soil, failure to account for the retention of each year's fallout on the surface of the soil probably accounts for the very high estimates of soil loss produced by other investigators.

The Australian empirical model provides estimates of soil loss an order of magnitude lower than the estimates provided by the USLE, the other two ^{137}Cs models and the empirical model of Ritchie *et al.*. (1974). This lack of agreement in the Australian model is disturbing and difficult to explain. The other models give answers that are reasonably consistent with the USLE and with the dissected and obviously seriously eroded condition of the land. In contrast the very low estimate of soil loss obtained from the empirical model appears to contradict the visual evidence from the site and must raise questions as to the reliability of this model.

CONCLUSIONS

Estimation of soil erosion from the depletion of fallout ^{137}Cs in the soil is probably the only physically-based technique that can be used instead of the USLE for estimating the topsoil erosion component of sediment budgets. However, in this investigation estimates of soil loss obtained using ^{137}Cs data have been found to be highly variable, ranging from 1.2 to over 100 t ha^{-1} year^{-1} depending on the assumptions and methods used. Soil loss estimates based on ^{137}Cs measurements have generally been much higher than USLE estimates. This is believed to be caused by failures of the linear and mass balance models to account for initially high concentrations of fallout on the surface of the soil. Estimates of soil loss using the Australian derived empirical model (1.2 t ha^{-1} $year^{-1}$) were an order of magnitude lower than estimates made using the USLE or other ^{137}Cs models and indicate that there may be serious problems associated with this model.

Confidence in soil loss estimates from ^{137}Cs data will only be achieved after each method has been calibrated against reliable erosion plot data. This must remain the highest priority in investigating the use of ^{137}Cs for estimating soil erosion

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REFERENCES

Campbell, B. L., Elliott, G. L. & Loughran, R. J. (1986a) Measurement of soil erosion from fallout of 137 Cs. *Search* **17** (5-6), 148-149.

Campbell, B. L., Loughran, R. J., Elliott, G. L., & Shelly, D. J. (1986) Mapping drainage basin sediment sources using caesium-137. In: *Drainage Basin Sediment Delivery* (Proc.Albuquerque Symp., August 1986), 437-446. IAHS Publ. no. 159.

Edwards, K. (1980) Runoff and soil loss in the wheat belt of New South Wales. In: *Proc. Agricultural Engineers Conf.* (Geelong), 94-98.

Edwards, K. (1985) Preliminary analysis of runoff and soil loss from selected long term plots in Australia. In: *Soil Erosion and Conservation* (ed. by S. A. El Swaify, W. C. Moldenhauer & A. Lo), 574-584. Soil Conservation Society of America, Ankeny, Iowa.

Kachanoski, R. G., & De Jong, E. (1984) Predicting the temporal relationship between soil cesium-137 and erosion rate. *J. Environ. Qual.* **13** (2), 301-304.

Longmore, M. E., O'Leary, B. M., Rose, C. W. & Chandica, A. L. (1983) Mapping soil erosion and accumulation with the fallout isotope caesium-137. *Austral. J. Soil Res.* **21**, 373-385.

Ritchie, J. C., Spraberry, J. A. & McHenry, J. R. (1974) Estimating soil loss from the redistribution of fallout 137 Cs. *Soil Soc. Am. Proc.* **38**, 137-139.

Pennock, D. J. & De Jong, E. (1987) The influence of slope curvature on soil erosion and deposition in hummock terrain. *Soil Sci.* **144** (3), 209-217.