Use of fallout ^{137}Cs measurements for validating and calibrating soil erosion and sediment delivery models

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Abstract Recent developments in soil erosion and sediment yield modelling have largely focused on the use of distributed models. Such models permit both the spatial heterogeneity of catchment land use, soil properties and topography and the spatial interaction of erosion and sediment delivery processes to be represented. An important constraint on these developments has, however, been the lack of data for validating the spatial distribution of erosion and deposition rates within a catchment predicted by the model. The use of fallout ^{137}Cs affords a means of assembling information on longer-term rates and patterns of erosion and deposition within a catchment which can be used to validate existing erosion and sediment delivery models and to develop and calibrate improved modelling strategies. This paper presents some preliminary results from a detailed investigation of erosion and sediment delivery within a 6.7 ha cultivated field in Devon, UK. Caesium-137 measurements have been used to estimate the rates and spatial patterns of erosion and deposition within this field and this information could be used for model testing and validation. To explore further the potential for using the ^{137}Cs data to calibrate distributed erosion and sediment delivery models, the spatial distribution of measured ^{137}Cs inventories within the study area has also been used directly, to calibrate a simple topography-driven soil erosion model superimposed onto a digital elevation model of the study area.

INTRODUCTION

Recent advances in the development of improved catchment-based soil erosion and sediment yield models have largely involved the use of distributed models (e.g. Lane & Nearing, 1989; Morgan *et al.*, 1992; Moore *et al.*, 1993; Ferro & Minacapilli, 1995; De Roo *et al.*, 1996; Young *et al.*, 1987; Wicks & Bathurst, 1996; Zhang *et al.*, 1996). Use of a distributed approach permits both the spatial heterogeneity of catchment land use, soil properties and topography and the spatial interaction of erosion and sediment delivery processes to be represented. An important constraint on such developments has, however, been the lack of data for validating the predictions of erosion and deposition rates *within* a catchment. Validation of such models is commonly restricted to comparison of predicted and measured outputs from the catchment in terms of storm hydrographs and associated sedigraphs and longer-term sediment yields. Close agreement of modelled and measured outputs will afford some degree of validation, but it will not provide conclusive confirmation of the validity of the internal functioning of the model and thus of the predicted erosion and deposition rates. Close correspondence between observed and predicted outputs could, for example, still be obtained in situations where the erosion and deposition rates predicted by the model differed substantially from the actual values. Future refinement and development of distributed erosion and sediment yield models will depend heavily on the availability of a means of validating the spatial patterns of erosion and sediment deposition rates predicted by the models. The use of fallout ^{137}Cs measurements to quantify soil redistribution within a catchment affords one means of assembling information on longer-term rates and spatial patterns of erosion and deposition within a catchment which could be used to validate existing erosion and sediment delivery models and to develop and calibrate new modelling strategies.

The use of ^{137}Cs measurements to estimate medium-term rates of soil erosion and sediment deposition within a field or a catchment (cf. Ritchie & McHenry, 1990; Walling & Quine, 1992, 1995) is commonly founded on comparison of the ^{137}Cs inventories at individual sampling points within a study area with a reference inventory representing the local fallout input and thus the inventory to be expected at a site experiencing neither erosion nor deposition. A ^{137}Cs inventory for an individual sampling point which is less than the reference value is indicative of erosion, whereas an inventory greater than the reference value is indicative of deposition. Estimates of erosion and deposition rates can be derived from the measured inventories. Advantages of the ^{137}Cs technique include the potential to derive retrospective estimates of medium-term rates of erosion and deposition based on a single site visit and to assemble spatially distributed information for individual points in the landscape, which can be used to study spatial patterns of soil redistribution.

The potential for using ^{137}Cs data to calibrate and validate distributed soil erosion and sediment delivery models has been recognized by several workers in recent years (e.g. De Roo & Walling, 1994; Chappell, 1996; Ferro, 1997), but most existing applications have employed estimates of soil redistribution rates derived from the ^{137}Cs measurements using various conversion procedures or algorithms. However, since the validity and reliability of the erosion and deposition rates derived from the ^{137}Cs measurements are heavily dependent upon the conversion procedures used and the assumptions involved (cf. Walling & Quine, 1990), some uncertainty must inevitably exist when evaluating and interpreting differences between these values and model predictions. A better approach to validating or calibrating soil erosion models could involve direct comparison of the measured ^{137}Cs data with predictions provided by the soil erosion model, by developing or extending that model to incorporate ^{137}Cs redistribution. This paper presents some preliminary results from a detailed investigation of erosion and sediment delivery processes in a small cultivated area at Higher Walton Farm near Crediton, Devon, UK, aimed at exploring further the potential for using ^{137}Cs measurements for model calibration and validation. Rates and spatial patterns of erosion and deposition within the study area have been estimated from an intensive programme of soil sampling and associated ^{137}Cs measurements. The ^{137}Cs data have also been used directly to calibrate a simple topography-driven soil erosion and sediment delivery model, superimposed onto a digital elevation model of the area.

FIELD AND LABORATORY PROCEDURES

The study area selected for this investigation is a cultivated field at Higher Walton Farm. This field has an area of *c.* 6.7 ha. To document the spatial distribution of

^{137}Cs inventories in the study field, bulk soil cores were collected from the field at the intersections of a 20 m grid, using a motorized percussion corer equipped with a 6.9 cm diameter core tube. In addition to the grid-based sampling, additional soil cores were collected from areas characterized by marked topographic change, in order to increase the representativeness of the sampling. In total, 165 bulk soil cores were collected from the study site. The corer penetrated to a depth of *c.* 60 cm and a small sample was collected from the base of each core for subsequent radionuclide assay, in order to ensure that the core had penetrated to the full depth of the ^{137}Cs profile. To provide additional information on the vertical profile of ^{137}Cs activity and the plough depth for the field, two soil cores were collected from a ridge and a depression near the bottom of the field for sectioning, using a larger 12 cm diameter core tube. A detailed topographic survey of both the coring locations and the entire field was undertaken in parallel with the coring programme, using an electronic theodolite. These survey data were used to create a DEM of the field for use in subsequent data analysis and modelling. All bulk cores and other samples were air dried, ground and homogenized prior to measurement of their ^{137}Cs content by gamma-spectrometry. The measurements were undertaken using high resolution coaxial HPGe detectors. Caesium-137 concentrations were obtained by measuring the activity at 662 keV. Count times were typically *c.* 10 h and produced values of ^{137}Cs activity with a precision of *c.* ±10% at the 95% level of confidence.

DOCUMENTING THE SPATIAL PATTERN OF SOIL REDISTRIBUTION RATES USING ^{137}Cs MEASUREMENTS

Figure 1(a) depicts a DEM of the study site at Higher Walton Farm created from the surveyed elevation data using the cell-based modelling tool of the ARC/INFO GIS. The height data were expressed relative to an arbitrary datum. Figure 1(b) shows the interpolated distribution of ^{137}Cs inventories within the field based on the measurements undertaken on the bulk soil cores. Significant spatial variability exists in these inventory values. Areas with reduced ^{137}Cs inventories are found along the ridge top and valley side, whilst areas located in depressions along the valley bottom are characterized by higher ^{137}Cs inventories.

Many approaches have been employed to convert ^{137}Cs measurements into quantitative estimates of erosion and deposition rates for cultivated soils (cf. Walling & Quine, 1990). These existing methods include both empirical relationships and theoretical models and accounting procedures. Of these approaches, use of a mass balance model is arguably the most reliable and in this study the mass balance model described by Walling & He (1977) has been employed to estimate the soil redistribution rates from the ^{137}Cs inventories obtained for the sampling points in the study field. This model provides a more realistic representation of the fate of ^{137}Cs in cultivated soil than many other mass balance algorithms, since it takes account of the fate of freshly deposited fallout, before its incorporation into the plough layer by cultivation. The resulting spatial distribution of soil redistribution rates within the study field is illustrated in Fig. 2. The mean erosion rate for the eroding areas was estimated to be 1.01 kg m^{-2} $year^{-1}$ (or 10.1 t ha^{-1} $year^{-1}$) and the mean deposition rate for depositional areas was 0.70 kg m^{-2} $year^{-1}$ (or 7.0 t ha^{-1} $year^{-1}$). The data presented

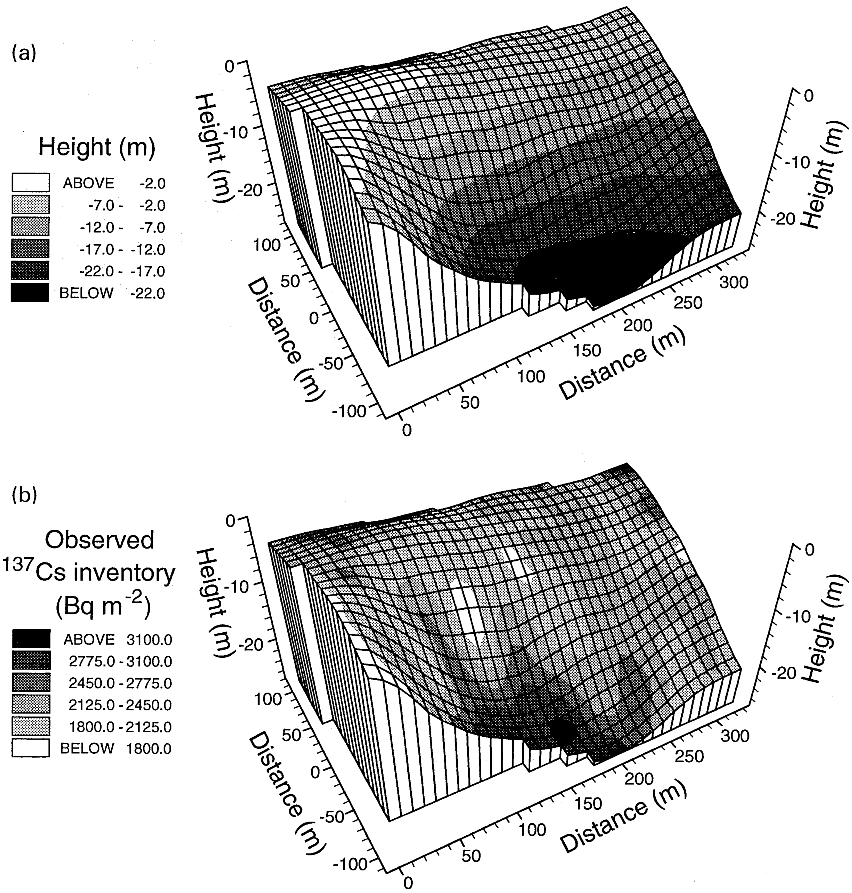

Fig. 1 A DEM of the study area (a) and the spatial distribution of measured ^{137}Cs in the study area (b).

in Fig. 2 could afford an effective basis for validating existing soil erosion and sediment delivery models in terms of assessing their ability to replicate both the pattern and the absolute magnitude of the erosion and deposition rates. It would, however, be necessary to recognize that the estimates of erosion and deposition rates derived from the ^{137}Cs inventories represent long-term averages (i.e. *c.* 40 years) and that any model being tested would need to be run for a long period or with synthetic input data which were representative of the longer-term. Furthermore, it should also be emphasized that the estimates of erosion and deposition rates derived from the ^{137}Cs measurements are heavily dependent on the validity of the conversion procedure employed and in this context it should be recognized that the mass balance model employed here only considers the role of water erosion in soil and ^{137}Cs redistribution. It is now generally accepted that tillage will also result in the redistribution of soil and therefore ^{137}Cs (cf. Lindstrom *et al.*, 1992; Govers *et al.*, 1994), and the role of tillage should be incorporated into the mass balance model if more precise estimates of soil redistribution rates associated with water erosion are required (cf. Quine *et al.*, 1996).

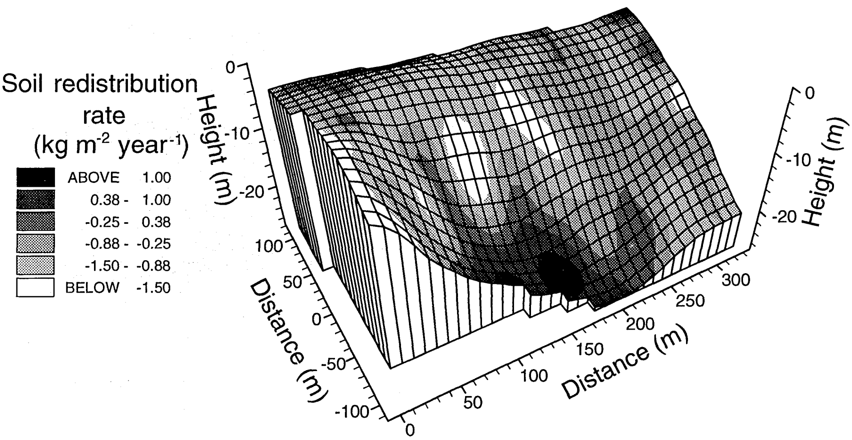

Fig. 2 The spatial distribution of soil redistribution rates within the study area derived from the ^{137}Cs data using a mass balance approach.

CALIBRATING AND VALIDATING A SIMPLE TOPOGRAPHY-DRIVEN SOIL EROSION MODEL USING ^{137}Cs MEASUREMENTS

The magnitude and spatial distribution of contemporary ^{137}Cs inventories within an area will reflect the cumulative effect of ^{137}Cs redistribution in association with soil movement, over the period since this radionuclide was introduced into the environment. It is therefore possible to use information on ^{137}Cs inventories to calibrate and validate soil erosion and sediment delivery models directly, if such models can be extended to simulate ^{137}Cs redistribution as well as soil redistribution. In the present study, water erosion and tillage redistribution have been assumed to be the primary processes controlling the movement of soil particles and ^{137}Cs within the study field and these processes have been incorporated into a topography-driven soil erosion and sediment delivery model which is capable of simulating the magnitude and spatial pattern of contemporary ^{137}Cs inventories within the field. By comparing the measured and simulated ^{137}Cs inventories, it is possible to calibrate this model and to assess its capability to replicate the measured values and therefore to provide meaningful estimates of soil redistribution rates.

A topography-driven soil erosion model incorporating water erosion and tillage

Along with rainfall erosivity and soil physical and chemical properties, topography can be expected to exert a primary control on soil erosion and sediment delivery (cf. Moore & Burch, 1986). Based on work reported by Kirkby *et al.* (1987), Govers *et al.* (1996) have proposed the following topography-driven transport-limited sediment transport function representing soil redistribution by both water erosion and tillage:

$$F_Q = \phi_1 (\sin\beta)^m S^n + \phi_2 \sin\beta \quad (1)$$

where F_Q (kg m^{-1} year^{-1}) is the sediment flux exported from a unit contour length downslope, β (°) is the angle of steepest slope, S (m^2) is the upslope contributing area, and m and n are constants. The first term on the right side of equation (1) represents sediment transported by overland flow and the second term sediment transported by tillage movement. Values of the constants ϕ_1 and ϕ_2 are dependent on the cultivation methods, rainfall regime, soil properties and the unit system adopted. When the values for m, n, ϕ_1 and ϕ_2 are known, the net soil redistribution rate R_{Net} (kg m^{-2} year^{-1}) can be calculated as the gradient of the sediment transport flux. For a point within a study area, R_{Net} incorporates both tillage and water erosion contributions and can be expressed as:

$$\begin{aligned} R_{Net} &= R_T - R'_T + R_W && \text{for a point experiencing water erosion} \\ R_{Net} &= R_T - R'_T - R'_W && \text{for a point experiencing deposition by water} \end{aligned} \tag{2}$$

where R_T (kg m^{-2} year^{-1}) is the rate of tillage-induced downslope soil removal from the point and R'_T (kg m^{-2} year^{-1}) is the rate of tillage-induced deposition of soil from upslope areas. In equation (2), R_W (kg m^{-2} year^{-1}) is the water-induced erosion rate for a point experiencing erosion by water and R'_W (kg m^{-2} year^{-1}) is the water-induced deposition rate for a point experiencing deposition by water, respectively. For complicated three-dimensional natural terrain, calculation of the various rates can be accomplished using the powerful modelling tools in a GIS software package such as ARC/INFO.

Modelling the spatial distribution of ^{137}Cs in cultivated soils using a mass balance approach

Once the basic soil erosion model has been formulated, the spatial distribution of ^{137}Cs within the study area can be modelled. The process of soil redistribution by tillage differs from that by water in that the former only produces movement of soil particles over a short distance, while the latter can transport the mobilized sediment over much longer distances. Sediment export from a field will only be associated with surface runoff. For a specific point, the upslope ^{137}Cs input flux $f_{T,In}(t)$ (Bq m^{-2} year^{-1}) and the downslope output flux $f_{T,Out}(t)$ (Bq m^{-2} year^{-1}) associated with tillage can be expressed as:

$$\begin{aligned} f_{T,In}(t) &= R'_T C'_T(t) \\ f_{T,Out}(t) &= R_T C_T(t) \end{aligned} \tag{3}$$

where t (year) is time and $C'_T(t)$ (Bq kg^{-1}) and $C_T(t)$ (Bq kg^{-1}) are the concentrations of ^{137}Cs in deposited and exported sediment respectively.

For a point experiencing water erosion, the ^{137}Cs output flux $f_{W,Out}(t)$ (Bq m^{-2} year^{-1}) can be written as:

$$f_{W,Out}(t) = R_W C_W(t) \tag{4}$$

where $C_W(t)$ (Bq kg^{-1}) is the ^{137}Cs concentration in exported sediment. Following Walling & He (1997), variation of the ^{137}Cs inventory $A(t)$ (Bq m^{-2}) with time for a point experiencing water erosion can be expressed as:

$$\frac{dA(t)}{dt} = (1-\Gamma)I(t) + R'_T C'_T(t) - R_T C_T(t) - R_W C_W(t) - \lambda A(t) \quad (5)$$

where $I(t)$ (Bq m^{-2} year^{-1}) is the annual atmospheric ^{137}Cs deposition flux and λ (year^{-1}) is the decay constant of ^{137}Cs. In equation (5), Γ represents the percentage of the freshly deposited ^{137}Cs fallout removed by water-induced erosion before being mixed into the plough layer. If an exponential distribution for the initial distribution of ^{137}Cs fallout at the surface of the soil profile can be assumed, following Walling & He (1997), Γ can be expressed as:

$$\Gamma = \gamma(1 - e^{-R_W/H}) \quad (6)$$

where γ is the proportion of the annual ^{137}Cs fallout susceptible to removal by erosion, and H (kg m^{-2}) is the relaxation mass depth of the initial distribution of fallout ^{137}Cs in the soil profile. Because the deposition of ^{137}Cs from the atmosphere is primarily associated with wet precipitation, a fraction of the annual ^{137}Cs input may be removed from the soil surface by water erosion associated with surface runoff before being incorporated into the plough layer by cultivation. γ is therefore dependent on the timing of cultivation and the local rainfall regime and has a maximum value of 1.0. (cf. Walling & He, 1997). For a point with water-induced deposition, the water-induced ^{137}Cs input flux $f_{W,In}(t)$ (Bq m^{-2} year^{-1}) can be written as:

$$f_{W,In}(t) = R'_W C'_W(t) \quad (7)$$

where $C'_W(t)$ (Bq kg^{-1}) is the ^{137}Cs concentration in deposited sediment. Variation of the ^{137}Cs inventory $A(t)$ with time at a point experiencing deposition by water can be expressed as:

$$\frac{dA(t)}{dt} = I(t) + R'_T C'_T(t) - R_T C_T(t) + R'_W C'_W(t) - \lambda A(t) \quad (8)$$

If it is assumed that the ^{137}Cs contained within the plough layer is uniformly distributed within the plough depth D (kg m^{-2}), the ^{137}Cs concentration $C_s(t)$ (Bq kg^{-1}) of soil within the plough layer can be expressed as:

$$C_s(t) = \begin{cases} \dfrac{A(t)}{D} & \text{for a net erosion point} \\ \dfrac{1}{D}[A(t) - \dfrac{|R_{Net}|}{D}\displaystyle\int_0^{t-1} A(t')e^{-\lambda t'}dt'] & \text{for a net deposition point} \end{cases} \quad (9)$$

For tillage erosion, the ^{137}Cs concentration of the deposited or exported sediment at a specific point may be assumed to be the same as that of the soil within the plough layer. However, for a point experiencing water erosion, the removal of the ^{137}Cs essentially comprises two components, the first of which is associated with the removal of the freshly deposited ^{137}Cs, and the second is associated with erosion of the accumulated ^{137}Cs stored in the soil. For a point experiencing water-induced deposition, the ^{137}Cs content of the deposited sediment reflects the combination of sediment and its associated ^{137}Cs mobilized from all the eroding areas that contribute to the aggrading point, and can be estimated from the erosion rates and the ^{137}Cs concentrations of the sediment mobilized from the upslope eroding area S_e (m^2). The ^{137}Cs concentration of mobilized sediment can therefore be expressed as follows:

$$C_T(t) = C'_T(t) = C_s(t)$$
$$C_W(t) = C_s(t) + \frac{I(t)}{R_W}\gamma(1 - \mathrm{e}^{-R_W/H}) \tag{10}$$
$$C'_W(t) = \frac{\int_{S_e} R_W C_W(t)\mathrm{d}S_e}{\int_{S_e} R_W \mathrm{d}S_e}$$

Calibration of the soil erosion model using the ^{137}Cs data

The algorithms for modelling the spatial distribution of ^{137}Cs inventories described above and the ^{137}Cs inventory data collected from the cultivated field at Higher Walton Farm have been used to calibrate the sediment transport model outlined previously using a GIS cell-based modelling technique. When a study area is divided into cells and the mobilized sediment is assumed to move down the slope gradient (or flow direction, defined as the direction of steepest slope), the sediment transport equation presented as equation (1) can be used to establish a cell-based soil redistribution model: the difference between the amount of sediment exported from a cell Q_{Out} (kg year^{-1}) and the amount of sediment transported into the cell from the neighbouring cells Q_{In} (kg year^{-1}) will reflect the net soil loss or gain for the cell. The net soil redistribution rate R_{Net} can be calculated as:

$$R_{Net} = (Q_{Out} - Q_{In}) / a \tag{11}$$

where a (m^2) is the area of the cell. A positive value of R_{Net} implies net soil erosion and a negative value deposition. Values for the two exponents m and n in equation (1) can be derived experimentally (cf. Desmet & Govers, 1995). To evaluate the optimum values for the two constants ϕ_1 and ϕ_2 in equation (1), the predicted ^{137}Cs inventory A_P (Bq m^{-2}) can be linearly related to the measured ^{137}Cs inventory A_M (Bq m^{-2}) with the tangent of the slope equal to 1.0:

$$A_P = \phi_3 A_M \tag{12}$$

with $\phi_3 = 1.0$.

In the present study, terrain attributes such as slope angle, flow direction and contributing area were derived from the DEM of the study area using the cell-based modelling tool in ARC/INFO GIS. These topographic attributes were then used to calculate soil redistribution rates. Values for m and n were set at 1.2 and 1.4 respectively, based on values reported by other workers (cf. Moore *et al.*, 1993; Desmet & Govers, 1995; Govers *et al.*, 1996). It has been assumed that the topographic change at the study site over the past 40 years has been insignificant and that erosion and deposition rates have been essentially constant through time. Different values for ϕ_1 and ϕ_2 were input into the topography-driven erosion model and values for R_{Net}, R_T, R'_T, R_W and R'_W were then calculated. The calculated soil redistribution rates were then input into the model describing the redistribution of ^{137}Cs within the field, and the model was run to simulate the spatial distribution of ^{137}Cs inventories. Values of other parameters required by the model were estimated based on information on local soil and rainfall conditions (215 kg m^{-2} for plough depth D, 5 kg m^{-2} for H and 0.30 for γ), and the temporal variation of the atmospheric ^{137}Cs fallout flux was assumed to be the same as that for Milford Haven, UK (cf. Cambray *et al.*, 1989), with the magnitude adjusted according to the estimated local reference inventory. Values of ^{137}Cs inventory were extracted from the simulated spatial distribution of ^{137}Cs inventories for those cells with the same coordinates as the sampled soil cores and compared with the measured ^{137}Cs inventories. The degree of agreement between the simulated and measured ^{137}Cs inventories was assessed using the correlation coefficient and the values of ϕ_1 and ϕ_2 producing the highest correlation coefficient were considered to be their optimum values.

Figure 3 presents the spatial patterns of ^{137}Cs inventories and soil redistribution rates within the study area predicted by the calibrated models and Fig. 4(a) depicts the relationship between the measured and model-predicted ^{137}Cs inventories (with

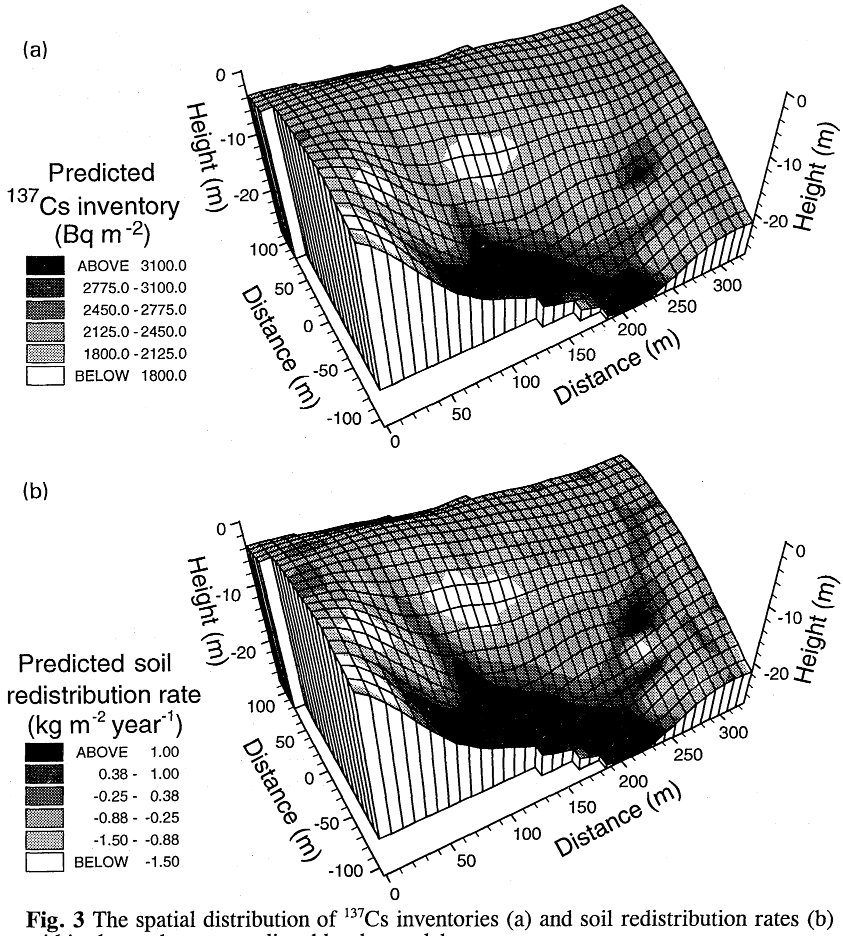

Fig. 3 The spatial distribution of ^{137}Cs inventories (a) and soil redistribution rates (b) within the study area predicted by the model.

optimum values of 1.9 for ϕ_1 and 210 for ϕ_2, with $r^2 = 0.29$). In general, there is a linear relationship between the predicted and measured ^{137}Cs inventories, confirming the validity of using ^{137}Cs data to calibrate this distributed sediment transport model. Figure 4(b) shows the relationship between the predicted ^{137}Cs inventory and soil redistribution rate for the study area. This differs from that associated with the conventional models used to estimate soil redistribution rates from ^{137}Cs measurements, in that the ^{137}Cs inventory is a multiple value function of the erosion rate for the model presented here, but a single value function for the conventional

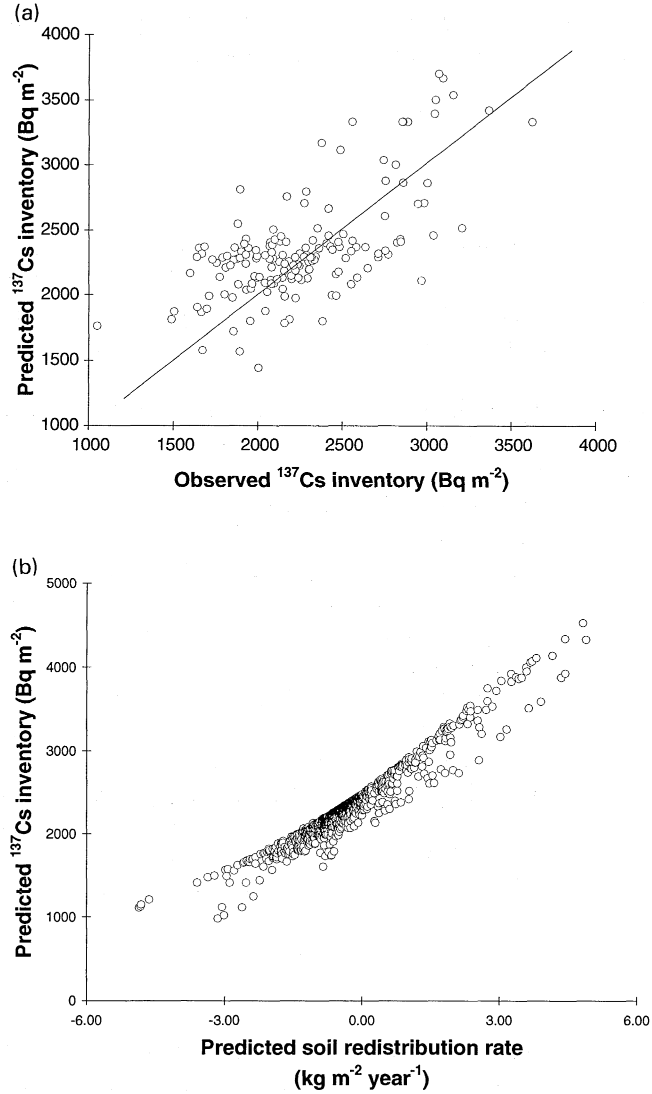

Fig. 4 The relationships between (a) model-predicted and measured ^{137}Cs inventories for the sampling sites in the study area (the smooth line is the theoretical line from Equation 12) and (b) the model-predicted ^{137}Cs inventories and soil redistribution rates for the study area.

models (cf. Walling & Quine, 1990). The relationship illustrated in Fig. 4(b) reflects the influence of both water erosion and tillage in redistributing soil on arable land and their relative importance will vary between sampling points. The level of agreement between the model-predicted ^{137}Cs inventory and the measured ^{137}Cs inventory must be seen as relatively low, and this may reflect the failure of the present model to represent fully the processes of soil and ^{137}Cs redistribution operating at the study site. Some inaccuracies may also be associated with the DEM of the study area derived from the surveyed elevation data using a GIS. Extension of this analysis to include use of data for two study areas characterized by similar soil and land use, with the ^{137}Cs inventory data from one area being used to calibrate the model and that from the other area being used to validate the predicted ^{137}Cs inventories, would increase its rigour.

PERSPECTIVE

Although the conventional use of ^{137}Cs measurements to derive estimates of soil redistribution rates provides a relatively simple means of assembling information for testing and validating the performance of erosion and sediment delivery models, the value of such exercises will be heavily dependent upon the reliability of the estimates of soil redistribution derived from the ^{137}Cs measurements, which may be difficult to assess. An alternative approach to validating such models is presented here. This involves using the model to simulate the spatial distribution of ^{137}Cs inventories. The level of agreement between the observed and simulated ^{137}Cs inventories could provide a more meaningful basis for assessing the likely validity of the estimates of soil redistribution rates provided by the model and of the representation of the key soil redistribution processes by the model. The results of using this approach presented here must be seen as preliminary. The agreement between observed and simulated ^{137}Cs inventories presented in Fig. 4(a) is limited and the ability of the model to simulate soil redistribution rates therefore remains uncertain. Further work is required to establish whether the lack of agreement between observed and measured ^{137}Cs inventories reflects failure of the model to represent either soil redistribution processes or the associated ^{137}Cs redistribution, or both. Scope clearly exists to exploit further the potential for using ^{137}Cs measurements for model calibration, since the ability to use a small number of ^{137}Cs measurements as a form of "ground truth" to calibrate a model to take account of local factors such as soil erodibility and land management practices would represent an important advance.

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