A MODEL OF ^{137}Cs ACTIVITY PROFILE FOR SOIL EROSION STUDIES IN UNCULTIVATED SOILS OF MEDITERRANEAN ENVIRONMENTS

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Abstract

A model to simulate ^{137}Cs profiles in soils during the time in which they are being eroded is proposed. The model uses one parameter to characterise the cesium transference in the soil and another to express the erosion rate. To test the model, ^{137}Cs profiles of stable and eroded soils were collected at sampling sites located on semiarid and temperate slopes in the Central Ebro basin, Spain. The ^{137}Cs profiles, corresponding to uncultivated soils with natural vegetation cover, were simulated using this model. The ^{137}Cs inventories and profiles calculated with the model are very similar to those measured experimentally, and thus it is possible to calculate soil erosion rates in physiographically diverse Mediterranean environments.

Keywords: *Soil erosion; fallout ^{137}Cs ; modelling; uncultivated soils; Mediterranean slopes.*

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Introduction

Use of the technique based on fallout ^{137}Cs (Rogowski & Tamura, 1965) has played an important part in what we know about the erosion-sedimentation process in very different situations (Longmore *et al.* 1983; Sutherland, 1992; Foster *et al.*, 1994; Pennock *et al.*, 1995; Loughran & Elliott, 1996). The technique provide an estimate of the net rate of soil redistribution, erosion, deposition, or even no change, and has been used in the calculation of the soil erosion rate value for a specific point or in a specific area.

The erosion rate values are calculated from models that relate soil loss with cesium loss and which must, therefore, signify a specific isotope concentration profile at that point. This implicit assumption that there exists a specific profile of ^{137}Cs in the soil is important because erosion itself decreases the overall amount of the radioisotope linked to its depth distribution. Therefore application of different models to the same experimental values of total cesium inventory may give to very different erosion rate values (Walling & Quine, 1990).

However, the profile of ^{137}Cs is not of great importance for estimating erosion rate for cultivated soils. In this case, tillage produces a turned and mixed top layer, as deep as the plough itself, which homogenises the cesium concentration. Experimental measurements of the isotope concentration determine the average value in the profile, thus making it possible to establish, and fairly closely, a linear relationship between cesium loss and soil loss at that point (Brown *et al.* 1981; Kachanoski & De Jong, 1984).

Uncultivated soils show ^{137}Cs concentration profiles decreasing with depth (Chamard *et al.*, 1993; Arapis *et al.* 1997). In this case, for each unit of time the erosion will cause the overall amount of cesium to drop by a different value (Bernard *et al.* 1992) and it only seems possible to establish empiric relationships between cesium loss and erosion rate. Such a relationship was proposed by Ritchie and McHenry (1975).

In the mountainous semi-arid and temperate regions of Spain, there are large areas of uncultivated soils. These Mediterranean landscapes generally have sparse scrub or tree vegetation, and erosion is an important factor in soil degradation (Navas, 1993; García-Ruiz *et al.*, 1995; Lasanta *et al.*, 1995). Slopes that are greatly affected by water erosion are abundant in Aragón, in the Central Ebro basin (Navas & Machín, 1997). In this region, there exists a change in both climate and physiography from the central valley up to the Pyrenees range. Thus there are marked differences in erosion factors and in soil losses (Navas *et al.* 1997).

In this work we present the results of a study to quantify the erosion on uncultivated soils by applying a model of ^{137}Cs profile. Our aim is to develop a model adapted to the specific characteristics of Mediterranean environments where in addition to climate factors stoniness and vegetation covers greatly affect the spatial distribution of ^{137}Cs . To this respect, a large diversity in ^{137}Cs activities is found on slopes of the central part of the Ebro basin (Navas & Machín, 1991; Quine *et al.*, 1994) and this has implications to the quantification of soil erosion. Furthermore, Navas and Walling (1992) point out that in this environment information on the ^{137}Cs depth profiles is of interest, because high stone content may result in two very similar ^{137}Cs concentration profiles with different overall inventories.

To test our model, two locations with contrasting climatic and edaphic characteristics were selected. The sites for soil sampling were on the semi-arid slopes around Ejea de los Caballeros (Zaragoza) and the Pyrenean middle-height mountain slopes in Borau (Huesca). We developed a model that relates the isotope loss with the erosion rate and simulates the ^{137}Cs profiles for the time period in which the erosion was taking place, *a priori*.

Erosion Model

Basic model

The model is of compartmental type in which the soil is divided into horizontal layers of a specific thickness and with a homogeneous ^{137}Cs distribution in each compartment (Bunzl *et al.* 1994; Bunzl *et al.* 1995; Kirchner, 1998a). It is also supposed that there is a cesium transference between each pair of adjoining compartments, in which the isotope flux is proportional to the difference in concentration between the two compartments in question, the proportionality constant being a specific coefficient **D**.

In addition to the downward movement, the model also takes into account the ^{137}Cs deposition on the surface. This surface deposition is known in detail in certain parts of the world (e.g.. Blagoeva & Zikowsky, 1995). At medium latitudes in the Northern Hemisphere, the deposition shows a similar temporal evolution for ^{90}Sr and ^{137}Cs in the literature (EML, 1977; Ritchie & McHenry, 1990; Agudo & García, 1998). It can, therefore, be a fair approximation to assume that the same evolution should be adjusted to the existing points of reference, although the absolute values where according local climatic characteristics. According to this reason we have chosen a temporal evolution for cesium deposition described by Ritchie and McHenry (1990), modifying the absolute values by a multiplicative factor in order to adjust the predicted total inventory from the point of measurement.

The increases or decreases in concentration level due to ^{137}Cs fluxes are corrected by a volume factor of the layers. This volume is taken as the working volume for ^{137}Cs adsorption, which is considered to be the same as that occupied by the soil fraction with a grain size of less than 2 mm. The effective volume is related to the effective thickness of each layer by a reference area introduced in the equations as $a_{\text{eff}}(z)$. This term is important since the existing models do not take into account soil factors such as the stoniness in the Mediterranean soil environment.

Based on the above-mentioned conditions for the compartment model, lineal transfer and ^{137}Cs deposition, we have implemented a computer programme in BASIC. The

programme divides the soil into 50 horizontal compartments 1 cm thick and a time step of one month. Tests have shown that smaller values of compartment thickness and time step do not greatly alter the results. The monthly ^{137}Cs deposition on surface values is introduced as input variable and the coefficient **D** for movement of cesium from compartment to compartment is taken as one parameter.

Starting with initial conditions of null ^{137}Cs concentration in all compartments, the programme imposes a first monthly deposition on the surface, which is distributed homogeneously throughout the first compartment:

$$C(1, t) = C(1, t-1) + [d(t) / a_{\text{eff}}(1)] \quad (1)$$

With: $C(1, t)$ is the ^{137}Cs concentration at the first compartment at time t .

$d(t)$ is the ^{137}Cs activity deposited at the soil surface

$a_{\text{eff}}(1)$ is the effective thickness of the first compartment

This process of ^{137}Cs deposition on the surface and its distribution in the first compartment is repeated in each unit of time, its value varying in accordance with the data on the temporal evolution of the isotope deposition.

Taking into account the concentration reached in the first compartment as a consequence of this deposition, the programme calculates the cesium flux towards the adjoining compartment and the consequent drop in concentration in the first compartment:

$$C(1, t) = C(1, t-1) + [d(t) / a_{\text{eff}}(1)] - [1 / a_{\text{eff}}(1)] F[1 \rightarrow 2, t-1] \quad (2)$$

In the same way as in the first compartment, there exist in the remaining ones an entry flux, which increases the previous time's concentration

$$C(z, t) = C(z, t-1) + [1 / a_{\text{eff}}(z)] F[z-1 \rightarrow z, t-1] \quad (3)$$

and an exit flux which reduces it

$$C(z, t) = C(z, t-1) - [1 / a_{\text{eff}}(z)] F[z \rightarrow z+1, t-1] \quad (4)$$

From the ^{137}Cs concentrations found in each compartment, the programme calculates the decay of the isotope concentration in the time interval presently being considered, $\lambda = 0.023 \text{ yr}^{-1}$, thereby obtaining the new concentration in time t and the partial ^{137}Cs inventory.

The process is repeated for each time step, and each time includes deposition on the surface, the calculation of new concentrations in all compartments as a result of transfer between one compartment and another and the decrease in the concentrations as a result of radioactive decay. The repetition of the process is carried out from the time of the first cesium deposition, taken as 1954, until the time of collecting those samples. In order to compare with the measured values, the program calculates the mean ^{137}Cs concentration for each 5 cm depth increments.

The simulation results include 85% and 65% ^{137}Cs effective volume and with four **D** values for the period 1954 - 1998. The results are stable profiles of soils that have become normalised so that they all have the same total inventory of 400 mBq cm^{-2} . The distribution of the isotope inventory in the different layers depends on the transference coefficient **D**. Also, it is observed that values of the effective volume for ^{137}Cs adsorption have an effect on the variation of the partial radioisotope inventories in the soil profile. Thus, ^{137}Cs activities for 65% effective volume are found at deeper soil layers than for 85 %.

Erosion model

The above simulation of ^{137}Cs profiles at stable points can be further completed by an erosion term, in order to generate cesium profiles in eroded soils. All that has to be done is to introduce into the above model the loss of a thickness e of the uppermost soil layer for each unit of time, providing there is a constant rate of erosion. This thickness of lost soil per unit of time bears immediate relation to the rate of erosion, if the density of the surface layer is known.

In order to implement the erosion term in the above model it is necessary to recalculate the cesium activities in all the compartments for each unit of time, in each step of the programme. The recalculation is carried out taking into account the fact that the removal from the soil of a surface layer of thickness e is equivalent to change the concentration in the compartments. This change is done by subtracting from it the cesium lost on account of the thickness e loss and adding to it the cesium gained because of a thickness e increase in the compartment, in order to maintain the thickness of the layer.

In the first compartment,

$$C(1, t) = (1 / a(1)) [(a(1) - e) C(1, t) + e C(2, t)] \quad (5)$$

Where $a(1)$ is the thickness of the first layer

e is the thickness lost every time step

For each one of the remaining compartments the same process of recalculation is carried out, with its concentration decreasing in a term corresponding to cesium lost on account of thickness loss and increasing in another term corresponding to cesium gained by layer increasing. The cesium loss term per surface unit in each compartment is calculated by multiplying the thickness e by the concentration of the compartment itself whilst the gain term is calculated by multiplying the thickness e by the concentration of the bottom compartment. The calculation process for concentrations is repeated for every unit of time.

$$C(z, t) = (1 / a(z)) [(a(z) - e) C(z, t) + e C(z+1, t)] \quad (6)$$

The functioning of the programme with this additional condition is similar to what took place in the previous case. It includes steps corresponding, for each unit of time, to the deposition of ^{137}Cs on the surface, the transference of the isotope between compartments, a new estimate of concentrations due to erosion and correction on account of radioactive decay. This process is carried out with temporal steps from when the ^{137}Cs starts to be deposited on the surface until the date of the soil sampling.

Using this model we have calculated the ^{137}Cs profiles in soils at the end of 1998, for 85% and 65% ^{137}Cs effective volume values and three different values of the transference coefficient **D**. For each one of the values used for the coefficient **D** we have calculated both the partial inventory and the total inventory of ^{137}Cs at points where there has been a different rate of erosion. The value **D** establishes different profiles and total inventories in points that have the same rate of erosion. This is equivalent to saying that the results obtained indicate different rates of erosion for the same cesium loss in different soils. Also, it has been observed that the ^{137}Cs effective volume value modify both the radioisotope depth distribution and the total inventory. These changes are most important when values for the coefficient **D** are lower and for the coefficient **e** are higher.

Experimental profiles

In order to check that the results obtained with the proposed model serve to describe real situations we have collected soil profile samples from slopes of different edaphic and climatic characteristics in two regions of the southern central Pyrenees. The samples collected correspond to the Borau area, taken from mid-height mountain slopes of the Pyrenean Eocene formations of marls and sandstones, and to the Ejea area, taken from the foothills of the structural surfaces over limestone formation at intermediate level around the central Ebro basin (figure 1). On the southern orientated slopes of the Ejea area, with altitudes around 450 m a.s.l. and average annual rainfall of 350 mm, the soils are mainly Regosols. In Borau, the studied slopes are SW orientated, altitudes range between 1000 and 1050 m with average annual rainfall of 900 mm, and soil types are Leptosols and Regosols. The main physiographic characteristics and soil properties of the studied sites are summarized in Table 1.

Samples corresponding to stable soils have been collected at the end of 1998 both in Borau and in Ejea, 5 being taken from the first and 6 from the second site. The sites were selected as reference for the areas because they were undisturbed, almost level and had a mature and natural vegetation cover that protects the soil surface from erosion. In addition to this, sampling was also carried out in Borau on a slope with scrubland and sparse trees, with 4 sampling points, and in Ejea on a badly eroded slope, where 5 sampling points were established. At each location, the sampling points were close to the reference area of stable soils.

The sampling procedures best suited for Mediterranean environments as well as the preparation of samples -drying and sifting, grain size measurement, with fractions above and below 2 mm being separated out- are described in Navas (1995). The density of the fraction under 2 mm is calculated and also the percentage of the total volume taken up by this fraction every 5 cm deep. Ejea soils have an average stoniness of 35 % and bulk density ranging from 1.6 to 2 g cm⁻³ while the more organic soils of Borau have around 15 % stone content and lower bulk densities (0.90 – 1.12 g cm⁻³). Contents of clay, sand and silt, and organic matter were also measured. The relation between ¹³⁷Cs activities and the percentages of fine soil particles at different soil depths suggest that there is not preferential erosion of ¹³⁷Cs enriched particles.

The samples of the fraction under 2 mm are measured using gamma spectrometry with a Ge HP solid state detector in order to obtain the concentration of ¹³⁷Cs, from the number of counts under its photopeak of 662 Kev. The inventory corresponding to each layer is calculated by multiplying the ¹³⁷Cs concentration by the mass of soil under 2 mm.

The total inventories of ¹³⁷Cs obtained experimentally in stable soils have been 400 ± 25 mBq cm⁻² in Borau and 200 ± 20 mBq cm⁻² in Ejea. The total inventories corresponding to the sites sampled on the slopes of both regions have been, in every case, lower than those of

the respective sites of reference, corresponding with the existence of erosion in all the sampled sites.

Comparison of results and discussion

In order to validate the results from the model, the values of the simulated ^{137}Cs profiles are compared with those obtained experimentally. First of all, each reference ^{137}Cs profile measured in stable soils is compared with the simulated ones by running the programme, without the erosion term, with different values of parameter **D** and observing whether any of the profiles obtained has the same morphology as the measured one.

In figure 2, we see (values are represented at the bottom of each 5 cm depth layer) the measured Borau stable profiles and the simulated ones with the value of **D** being the best suited for running the programme with a ^{137}Cs effective volume of 85%. A remarkable correspondence between simulated and measured profiles can be observed, with the best values for **D** ranging from 0.062 to 0.150 $\text{cm}^2 \text{ month}^{-1}$. The results obtained for the same adjustment for the Ejea stable profiles are equally satisfactory.

The good correspondence between simulated and measured profiles is remarkable inasmuch it is obtained using solely generic ^{137}Cs deposition data and a single parameter, the transference coefficient **D**. The results could possibly be better if a ^{137}Cs transference coefficient variable according to depth was to be added to the model. Other additions could also be that of more complex isotope transference functions (Velasco *et al.* 1993; Kirchner, 1998b; Walling and He, 1999), or even dependency on the terrain properties (Hilton *et al.* 1993). Nevertheless, the excellent concordance between experimental and simulated data using a single parameter makes it unnecessary to add others and, in addition to enjoying greater simplicity, it provides information on the mechanism of ^{137}Cs transport in the soil, which seems to be primarily of a diffusive nature.

The comparison of the ^{137}Cs profiles measured in eroded soils with the model based ones is carried out by running the programme with different values of the **D** and **e** parameters until a simulated profile and total cesium inventory approaching the measured results at each site is obtained.

Figures 3 and 4 show the inventories and profiles obtained on the Borau and Ejea slopes that were simulated with the measured ^{137}Cs effective volume and with the best **D** and **e** values. In every case there exists a good agreement between the measured and simulated profiles. As in the case of the stable profiles, mention should be made to the good correspondence between experimental and simulated profiles. This is obtained by means of using only two parameters, **D** and **e**. This seems to indicate that the erosion being produced really is the one supposed in the model, and affecting the surface layer of the soil.

The following simulation procedure was used: values for **D** ranging between 0.130 and 0.180 on the Borau slope, and between 0.038 and 0.180, in $\text{cm}^2 \text{ month}^{-1}$, on the one in Ejea. Therefore, greater dispersion values found in Ejea may be due to larger differences in ^{137}Cs transference in these semiarid soils. The values for **D** are very similar to the **D** coefficient of dispersion values by Smith and Elder (1999) used to characterize the distribution of ^{137}Cs in soils by the advection-dispersion equation. The erosion factor values for **e** range from 0.003 to 0.016 cm in Borau, and from 0.004 to 0.015 cm in Ejea. These **e** values correspond with the erosion rates between 0.036 and 0.192 cm year^{-1} (between 3.2 and 21.4 $\text{Mg ha}^{-1} \text{ year}^{-1}$) in Borau and between 0.048 and 0.180 cm year^{-1} (between 8.5 and 33.5 $\text{Mg ha}^{-1} \text{ year}^{-1}$) in Ejea. In both cases, the factor values necessary for the simulation depend as much on the total inventory of the profile with respect to that of reference, between 40 and 84% in Borau and between 36 and 72% in Ejea, as on the ^{137}Cs transference coefficient in each profile. Therefore, the more mineral and stony soils of Ejea slopes have higher erosion

rates as it could be expected from a semiarid environment where less vegetated slopes (30% less than temperate Borau) are more prone to erosion.

In summary, we have compared the values of the experimental inventories obtained at all depths with those of the simulated inventories. The results of the correlation between the partial inventories for all the eroded sites in Borau and Ejea appear in figure 5. As can be seen, there is a linear correlation with a slope value noticeably equal to the unit, with a good correlation ($r = 0.973$). Considering Ejea and Borau separately, correlation coefficients are also highly significant ($r = 0.956$ and 0.978 , respectively).

Soils on slopes of Mediterranean environments generally have high stone contents. This soil property affects the effective volume for ^{137}Cs adsorption and thus two profiles with very similar ^{137}Cs concentrations and therefore similar shape may have different overall inventories. Therefore, in such stony soils a ^{137}Cs activity profile model would more accurately describe erosion on a site in comparison with data from just one overall inventory.

The model proposed in this work includes profiles that have been obtained *a priori*, not necessarily exponential and with morphologies dependent on edaphic and physiographic conditions. Despite it is based on simple hypotheses, generic data and small number of parameters, this model could match well with experimental data, and thus it is suitable to estimate erosion rates in soils under natural conditions on Mediterranean slopes.

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FIGURES

- 1.- Location of the Ejea and Borau study areas
- 2.- Measured and simulated ^{137}Cs activity profiles at stable sites in Borau slopes for an effective volume of 85%.
- 3.- Measured and simulated ^{137}Cs activity profiles at eroded sites in Borau slopes for an effective volume of 85%.
- 4.- Measured and simulated ^{137}Cs activity profiles at eroded sites in Ejea slopes for an effective volume of 65%.
- 5.- Linear regressions between measured and simulated ^{137}Cs activities at depth profiles of Ejea and Borau slopes.

Table 1. Main characteristics and soil properties in the studied sites of Ejea and Borau.

	Slope %	Vegetation Cover %	pH	E C dSm ⁻¹	CO ₃ ⁼ %	O M %	Sand %	Silt %	Clay %
Borau	40	25-60	8.0-8.2	0.1-0.3	30-45	2-4	15-30	45-55	15-20
Ejea	30	15-35	8.7-8.8	0.2-0.6	40-60	1.5-3	10-32	47-54	14-43

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5