COMPARISON OF MEASURED ^{137}CS DATA AND USLE/ RUSLE SIMULATED LONG-TERM EROSION RATES

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Abstract

The ^{137}Cs technique of quantifying soil erosion is used to provide field data to compare with the empirical model USLE/ RUSLE for predicting long-term erosion rates in afforested lands. Caesium-137 from atmospheric nuclear-weapons tests in the 1950s and 1960s, deposited worldwide on the land surface by precipitation, has become an important tool for assessing soil erosion and sedimentation in a wide variety of environments. The underlying hypothesis to support the use of ^{137}Cs measurements to estimate rates of erosion or sedimentation is the assumption that a reliable relationship can be established between the degree of increase or depletion of the soil caesium-137 inventory relative to the baseline or reference inventory and the total depth of soil loss or accumulation. The reference inventory is usually established by sampling adjacent, stable sites, where neither erosion nor deposition has occurred. Where sample inventories are lower than the local reference inventory, erosion may be inferred. Similarly, sample inventories beyond the reference level are indicative of deposition. Estimation of sediment production by erosion has traditionally been solved through the use of empirical models as USLE and its corrected version RUSLE (Renard et al., 1997), and extensive work has been done regarding calibration and validation of its main parameters under Uruguayan local conditions (Clérici y García Prèchac, 2001). The results of a trial run of the technique on Eucalyptus forested microcatchment (97 ha) are presented. The expected distribution of deposition was derived from the reference sample activity: 373,5 Bq/ m^2. Evidence of soil erosion in the catchment's middle slope was deduced whereas soil cores from the lower slope had more than expected activity indicating deposition. Results indicate a good agreement between the ^{137}Cs data and USLE/ RUSLE predicted erosion in the slope.

Keywords: erosion model; caesium-137; USLE.

Introduction

Since 1998 researchers from the Universidad de la República (UdelaR) Agricultural Engineering Network carry on investigation in connection with hydrological and environmental variables under different land uses, with a focus on soil and water resources in afforested areas. Micro-watersheds under diverse land uses and management practices were considered as case study units for which the most widespread-used hydrological variables were monitored and recorded, so to speak quantity and quality of rainfall and runoff waters, extreme storm events runoff peaks, distribution of rainfall and water interception, monitoring of water table levels, soil loss measurements in the watershed area.

Sedimentation processes originated by watershed soil erosion lead to particle deposits in streams and lakes beds, shrinking their hydrological regulation capability and jeopardizing water quality in terms of physical, chemical and microbiological properties. Moreover soil erosion plays a major role within the determination of the sustainability of agricultural practices given its direct and indirect influence on crop productivity and economical benefit. The interaction between weather conditions and agricultural practices is a key feature of soil loss due to erosion, and its relevance may be enhanced by means of increasing rainfall frequencies and amounts due to a global climate change scenario (SWCS, 2006).

The quantification of sediment production rates under erosion processes has traditionally been obtained through empirical-based models such as the USLE equation –or the improved RUSLE equation (Renard et al., 1997) –. This very model, subject of extensive parameter calibration proceedings aiming to adapt the equation to local conditions (Puentes, 1981; García Préchac et al., 1999; Terra y García Préchac, 2001, Clérici y García Préchac, 2001), has become the most widespread tool to determine soil sheet erosion rates in Uruguay.

In order to validate and apply any of the soil erosion models, field data must be collected. These pieces of information may either result from direct measurements of soil erosion or by calculating inventories of certain substances mixed in the soil masses, for instance radionuclides. More specifically the radionuclide technique consists of comparing the concentration of a selected isotope (by measuring the intensity of nuclear activity of a soil sample) at a site suspected of being affected by erosion or sedimentation with the inventory of a reference site. The most often selected radionuclides for this technique are ^{137}Cs (man-made, released into the atmosphere mainly in the 1950's as a consequence of the atomic trials), ^{210}Pb (natural, subproduct of the ^{238}U decay) and ^{7}Be (natural, introduced on the Earth from cosmic radiation).

Caesium-137 is found in association with the clay and organic matter, soil fractions that are more susceptible to erosion, becoming a good tracer for evaluating superficial erosion processes. Research by Menzel dating from the 1960's concluded that a correlation exists between soil erosion and decreases in radionuclide inventories, considering this fact Rogowski and Takamura (1965) establish an empirical relationship between 137Cs redistribution and soil loss by runoff and erosion. In the 1960's and 1970's a similar behaviour is detected by many researchers, featuring it as a soil erosion tracer (Zapata, 2002). Regarding South America countries, the application of the radionuclide technique is widespread (Andrello et al., 2003; Schuller et al, 2003; Schuller et al, 2006).

The measured ^{137}Cs inventories, and its corresponding spatial distribution throughout the study area, provide qualitative information of the relative rates of erosion or deposition involved. When soil erosion is evidenced at some area within the field, the ^{137}Cs inventory shall be smaller than its pair from the reference site. When sedimentation occurs instead, the greater the ^{137}Cs inventory is compared to the reference site, the more intense the sedimentation is. However, quantitative results are necessary in order to validate and apply any soil erosion model, hence the need for a conversion model.

Walling et al. (2003) introduces the different conversion models by classifying them into two categories. On one hand, the amount of soil loss can be obtained from an empirically-based regression model, whose equation parameters may be drawn from on-site long-term erosion-plot studies. Although once calibrated the model is easy to use, it will be applicable only under fixed space-time conditions and thus a periodic model update may be necessary.

On the other hand a series of theoretically based models are available, their main advantage being the lack of need of parameter estimation from empirical data prior to their implementation, and ranging –in terms of overall complexity– from simple proportional models –in which the amount of eroded soil is proportional to the reduction in the ^{137}Cs inventory– to more complex –yet less dependent on specific space-time conditions– mass-balance models, aimed at calculating the evolution of the ^{137}Cs inventory at a certain point taking as input ^{137}Cs fallout and both soil loss and sedimentation processes.

Materials and Methods

<u>Study Area</u>

The study area is located in the northwestern region of Uruguay, department of Río Negro, within the Río Negro river lower basin (Image 1). The operation of the 97 ha Santo Tomás 1 catchment for scientific research has been managed since 2007 by the Universidad de la República.

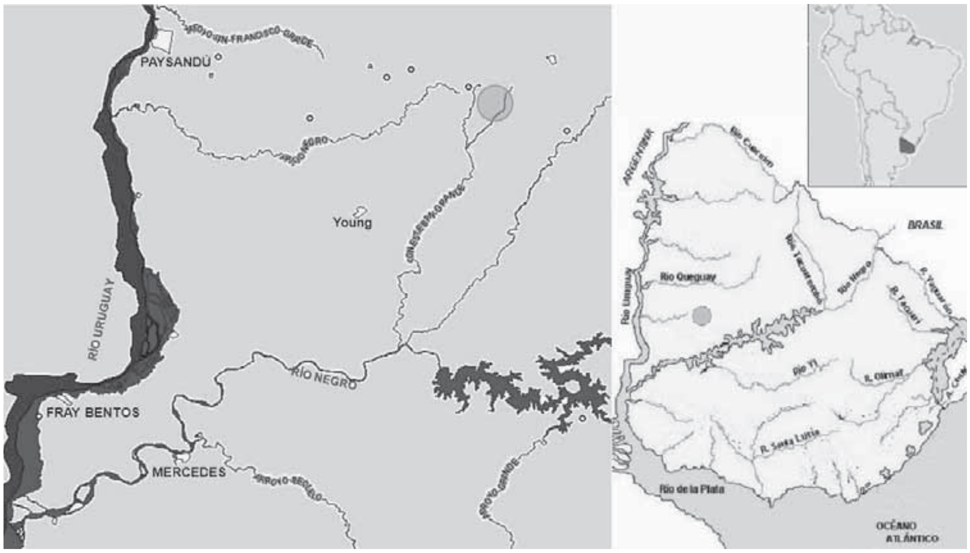

Image 1. Location of study area

Landscape is slightly undulating, elevation ranges from 103–110 m. Average basin slope is smooth (3-4%). The length of the stream throughout the basin is 1200 m, its mean slope 1% and the time of concentration is 25 minutes. The main geological formations are Mercedes-Asencio Formation, fine to medium sandstone cemented with carbonate, deposited in the Upper Cretaceous. The prevailing soils are of low fertility, derived from sandstone with clay cement (described above). The A horizon is a sandy loam texture with an average depth of 0.2 m, below it the B horizon consists of a sandy clay loam texture with an average depth of 0.8 m.

Vegetation cover was *Eucalyptus globulus*, planted during 1998 fall and spring with a density of 895 trees per hectare. Harvest was performed in conditions of high soil moisture during Nov/09 to Feb/10 (summer season).

Soil Sampling

The proper selection of reference sites is critical for successful implementation of the technique, and therefore a reference site must accomplish at least these conditions: 1) experienced neither soil loss nor sediment deposition; 2) vegetation remained unchanged since the beginning of the ^{137}Cs fallout in the early 1950s (perennial grass or low herb cover is best); 3) lacked alteration by human activities such as tillage. In order to meet these criteria a site was selected in a firebreak next to the catchment, under a high-voltage power line tower. For the case study, a slope transect in Santo Tomás 1 catchment was sampled before and after harvesting the 12 year old *Eucalyptus* plantation (Image 2), with an interval of four months in between.

Image 2. Soil sampling in the slope transect: upper (A); middle (B); lower (C).

Sampling was performed using 10 PVC cylinders 2'' diameter and 5cm high, hammered into the soil normal to the surface (Image 2). The content of the cylinders is directly transferred to a plastic sample bag by tapping the cylinder and using a knife because of the cohesiveness of the soil. Incremental 5 cm sampling is performed until the total depth is reached (30 cm).

Caesium-137 measurements

The conditioning and analysis of the samples was carried out at the Center for Nuclear Research laboratories (UdelaR). Once the sample arrives at the laboratory, a series of pre-analytical steps –described below– are carried out in order to prepare the sample for subsequent quantification of ^{137}Cs.

1. Weighing and air drying.
2. Oven drying (60 ºC).
3. Dry weight determination.
4. Milling of the soil sample.
5. Sieving the sample (2mm).

^{137}Cs activity in the collected soil samples was measured in a detector array of Germanium HPGe-ultrapure-Canberra. This detector was previously calibrated by two methods:

1. Standard ground provided by IAEA (MGS-5) in a 500g Marinelli container.
2. Simulation with Montecarlo code DETEFF 4.2 (N. Cornejo Diaz, M. Jurado Vargas)

Soil samples were placed in a Marinelli's container, weighed and measured for at least 24 hours. However, duration of activity measurements proved longer in the sample cases with lower ^{137}Cs inventories (up to 48 hours).

In the first place, reference site samples and study catchment samples were processed. Subsequently, the accounts for the peak corresponding to the energy 661.5 keV (^{137}Cs) were determined. Data processing was carried out in order to determine: depth profile of the reference site; key parameters of the conversion models (^{137}Cs – soil erosion) and ^{137}Cs activity in areas of study to date of interest.

Estimating rates of soil loss from 137Cs measurements

Use of caesium-137 measurements to estimate rates of loss and accretion is based on the assumption that a reliable relationship can be established between the degree of increase or depletion of the soil caesium-137 inventory relative to the baseline inventory and the total depth of soil loss or accretion. Walling and Quine (1990) recommend the application of theoretical accounting procedures to establish calibration relationships, because they represent the aggregate effect of all redistribution processes. Particularly mass balance models which take account of both inputs and losses of ^{137}Cs from the profile over the period since the onset of ^{137}Cs fallout, have been widely used. The selected model, among them, is the mass-balance model incorporating the influence of tillage displacement presented by Walling and He (1999). The results from this model are likely to be closer to reality for cultivated soils, considering that it can only be used for individual slope transects.

The model (named Mass-Balance Model III) was applied using the free available software Radionuclides Inventories Conversion (Walling and He, 2001). The key parameters used were: h_0: 128 kg m^{-2}; d: 301 kg m^{-2}; ϕ: 10 kg m^{-2} yr^{-1}; P:1. The slope transect length is 200m and 2.5º gradient.

USLE/RUSLE

To estimate soil loss in the slope through USLE-RUSLE the free available software EROSION 5.91 (Préchac Garcia et al, 2005) was used. Considering the location of the study area the R factor was established in 543 J.ha^{-1}, length and gradient of the slope makes an LS factor of 1.197. The length of the slope exceeds the maximum for the model's database, therefore factor P by default takes the value of 1. Assuming contour plowing as the soil management practice, factor C was established in 0.006 for the situation of a closed canopy Eucalyptus plantation. Factor K for the studied soil is 0.2 Mg J^{-1} and the soil tolerance for erosion is 7 t ha^{-1}.

Results

The obtained calibration curve for the HPGe detector resulted similar with both methods (IAEA and DETEFF), and efficiency for ^{137}Cs was performed by interpolation on the efficiency vs. energy relationship.

Once the detector is calibrated the reference site sample was measured, the total inventory of the sample was 367 Bq/m^2. The obtained depth-incremental profile (Image 3) shows the characteristic exponential depth distribution of ^{137}Cs concentration in undisturbed soils (Zapata, 2003), validating the election of the reference site.

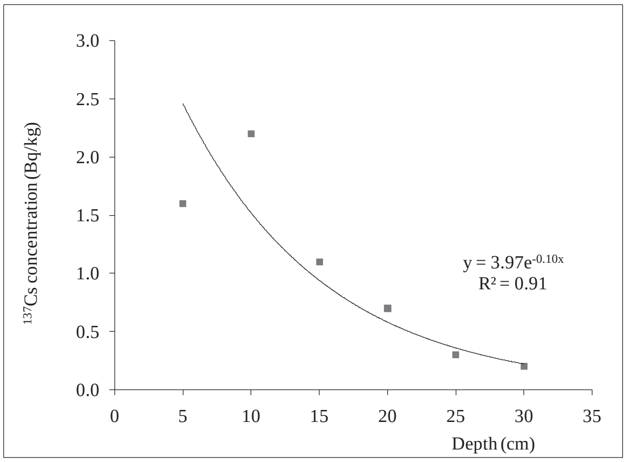

Image 3 - Depth-incremental profile recorded for the reference site.

Caesium-137 activity measurements report reduction, regarding the reference site, only in the middle slope position before harvest (Table 1). Neither erosion nor deposition is evident from measurements of samples performed after harvest, since percentage of change in total inventory is lower than the measurement technique error (15%).

Table 1: Measured soil ^{137}Cs in Santo Tomás 1 catchment.

	Measured soil ^{137}Cs (Bq/m^2)	
Slope position	Before harvest	After harvest
Upper	492	413
Middle	240	413
Lower	470	436

Image 4 compares the recorded ^{137}Cs distribution profiles for the reference site collected soil samples –undisturbed permanent pasture–, and for the Santo Tomás 1 catchment –forest cover 12-year-old eucalyptus– middle slope sample collected prior to the beginning of harvesting activities.

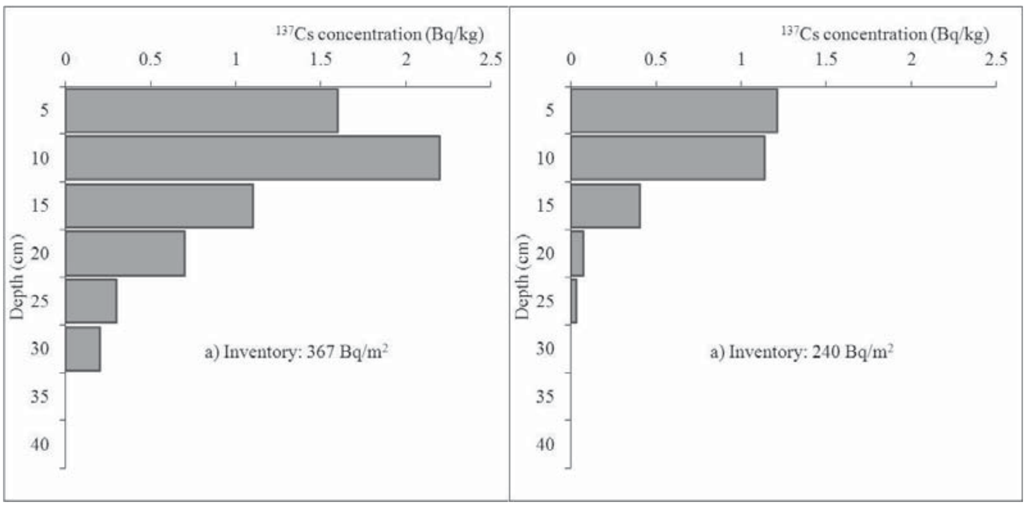

Image 4 – Comparison of ^{137}Cs profiles associated with soil samples collected from a) reference site, and b) middle slope site in Santo Tomás 1.

In both cases most of the inventory was found in the top 10-15 cm of the profile, with relatively little or none ^{137}Cs below 20 cm. In the middle slope site the depth distribution patterns indicate erosion given the reduction of ^{137}Cs activity. It also indicates that ^{137}Cs had been mixed within the plough layer by cultivation (20 cm) and the concentrations declined to near zero immediately below that depth.

Mass-balance model III was applied to the slope transect between middle and lower slope positions and considering the before harvest ^{137}Cs inventories. Results show a net erosion rate of 0.3 t ha^{-1} yr^{-1}, while the erosion rate obtained through the USLE was 0.78 t ha^{-1} yr^{-1}.

Conclusions

The viability and potential of the caesium-137 technique in Uruguayan afforested areas has been demonstrated by the results presented here. The obtained results in terms of net erosion rates fall within the expected range, given the characteristics of soil and vegetal cover and well below the referenced maximum soil erosion threshold.

The comparison between the net erosion rate obtained with de ^{137}Cs technique (0.3 t ha^{-1} yr^{-1}) and its similar from the USLE equation (0.78 t ha^{-1} yr^{-1}) shows a good fit although the assessed value is lower than the potential erosion rate that results from the USLE model. This application allows the establishment of a good alternative for the calibration to local conditions of the USLE-RUSLE parameters connected with land use and management.

Although the presented paper is the result of a trial run in determining erosion rates using the caesium-137 technique, it is believed that further improvement of the field work and laboratory methodologies could transform this technique in a powerful land management tool applicable in wider areas.

Acknowledgements

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