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A comparison of erosion rates obtained using the ^{137}Cs technique and direct measurements on runoff plots

VLADIA CORRECHEL[1], OSNY OLIVEIRA SANTOS BACCHI[1], ISABELLA CLERICI DE MARIA[2], SONIA CARMELLA FALCI DECHEN[2] & KLAUS REICHARD[1]

1 *Centre for Nuclear Energy in Agriculture, University of São Paulo, CP 96, CEP 13.400-970 Piracicaba, SP, Brazil*
vladia@cena.usp.br

2 *Campinas Agricultural Institute (IAC), CEP 13.020-902 Campinas, SP, Brazil*

Abstract Measured ^{137}Cs losses (Bq m^{-2}) from long-term runoff plots under tropical conditions and corresponding estimated soil erosion rates (Mg ha^{-1} year^{-1}) were significantly correlated with directly measured soil losses from the same plots, during the same period (1963–2002). A tendency for higher ^{137}Cs inventories to be found in soil profiles from the bottom third of the slopes could be explained by the restricting effect of the collector system on the outflow runoff or by tillage translocation. Despite the very low ^{137}Cs activity found, and the small number of plots analysed, the ^{137}Cs technique yielded consistent results, closely comparable with those obtained by the traditional direct measurements on long-term runoff plots.

Key words caesium-137; fallout; radioisotopes; radionuclide; sediment loss; soil erosion

INTRODUCTION

Water erosion is the most important environmental process of soil loss in tropical regions. Erosion affects agricultural productivity and its off-site impacts, such as increased sediment loads in rivers, sedimentation of conveyance systems and reservoirs, increased costs of water treatment, and sealing of irrigated soils, can significantly influence the quality of human life. Due to the wide-ranging importance of soil erosion and the need to evaluate the impacts of land use and the effectiveness of soil conservation measures, it is very important to know how to quantify erosion rates (Lal & Stewart, 1990). Among the direct methods available to quantify these rates are long-term runoff plots equipped with sediment collectors or wash traps. Such plots proved very useful in the past for the development and calibration of empirical prediction erosion models. Another technique which can be used to estimate soil erosion rates, and which has been in use in different countries since the 1970s, is the ^{137}Cs fallout redistribution method. Zapata *et al*. (2002) present a short review of the ^{137}Cs technique. More information can be found at http://hydrolab.arsusda.gov/cesium. Walling & Quine (1990, 1991, 1993) provide a useful review of the technique and its potential and limitations.

The ^{137}Cs fallout was greater in the 40–50° latitude band of both hemispheres and peak concentrations occurred in 1963 in the northern and in 1965 in the southern hemisphere. Once in contact with the soil surface layer, this radionuclide becomes strongly adsorbed by fine soil particles (Livens & Loveland, 1988). Since its translocation in the soil profile is extremely slow (Tamura, 1964), it is found mainly in the upper 10 cm soil layer of uncultivated soil under uneroded conditions, with an exponential decrease in activity with depth. Subsequent redistribution of the radionuclide reflects the movement of soil particles, since the ^{137}Cs remains adsorbed and moves in association with these particles.

If a relationship between soil ^{137}Cs concentration and soil loss or gain can be established, it should be possible to estimate soil erosion or deposition rates from ^{137}Cs concentration measurements. The first attempts to develop calibration relationships for use with ^{137}Cs measurements involved empirical relationships based on erosion rates measured on experimental plots and ^{137}Cs inventories of soil samples collected from the same plots (e.g. Ritchie & McHenry, 1975). The limitations of such empirical relationships are discussed by Walling & Quine (1993), the most important being the fact that they can only be applied to situations in which the local conditions, especially soil type and plough depth, are identical and where the time period involved is the same as that covered by the original plot measurements.

In view of the limitations of empirical calibration relationships, theoretical calibration models have been developed. The simplest and most widely used theoretical calibration model for cultivated soils is the proportional method. This model has several important advantages in relation to empirical calibration relationships; more particularly it can take account of time, local ploughing depth and soil bulk density. Thus, the model could be used over a wide range of conditions and time-scales. Despite the advantages in relation to empirical equations, this theoretical calibration model needs to be validated by comparison with some other direct methods of assessing erosion rates.

The main objective of this work was to validate the use of the ^{137}Cs technique for estimating erosion rates under tropical conditions, through comparison of the resulting estimates with erosion rates measured directly using runoff plots.

MATERIAL AND METHODS

The experimental area, which belongs to the Campinas Agricultural Institute (IAC), is located in Campinas, SP, Brazil (22°09′S, 47°01′W). The climate of the region (Cwa-Köppen) is sub-tropical and dry during the winter, and rainy during summer, with an average annual rainfall of 1400 mm. The study was carried out on eight long-term runoff plots, which have been operated and maintained by IAC since 1943. The soil of the area is an Oxisol (Typic Hapludox), one of the most representative soils of the State of São Paulo.

An uneroded reference site, located about 1 km from the runoff plots, was selected in order to establish the total local fallout input of ^{137}Cs. This site consists of a very flat 2400-m^2 area covered by a perennial legume, called "kudzu tropical" (*Pueraria phaseoloides* (Roxb.) Benth.). The area was sown only once in 1943 and the local soil has remained uncultivated since that time. Five profiles from this area were sampled using a depth incremental sampling procedure. The sampling device allows soil samples to be collected in 5-cm increments, down to 35 cm depth in the soil profile, covering a surface area of 672 cm which corresponds to a sampling volume of 3360 cm^3 for each 5-cm layer. The resulting soil samples were used for ^{137}Cs activity determination, as well as for chemical and physical analysis.

On each runoff plot, three soil profiles were sampled: one representative of the upper third of the plot length (U), another of the middle third (M) and one of the bottom third (B). Bulk samples from each profile were taken down to 60 cm depth in three layers of 20 cm thickness, using a 10-cm diameter Riverside auger. Since the installation of these runoff plots in 1943, each plot has received different crops and soil management practices that are described in more detail by Correchel (2004).

The main characteristics of each plot are:

(a) Plots 1–6 have an area of 100 m^2 (25 m long × 4 m wide) and plots 7 and 8 an area of 1875 m^2 (75 m long × 25 m wide).
(b) Plots 1–6 were used for testing different crop-rotation systems and all operations have been undertaken manually.
(c) On plots 1, 2 and 3, experiments involving crop rotation, application of organic residues and variation in crop canopy cover and mulch are being carried out.
(d) On plots 4, 5 and 6, different experiments involving of crop rotation and evaluation of different soil conservation practices are being carried out. Among these three plots, plot 6 received the worst management in terms of soil conservation and was maintained without any vegetation cover for a period of 11 years. The main difference between plots 4 and 5 is the total time period that they were maintained without vegetation cover. This period was much longer for plot 4.
(e) On plots 7 and 8, experiments involving evaluation of different soil tillage systems are being carried out. The main difference between these two plots and the others is that in both, the management operations were performed by mechanical equipment and the slopes were 6% lower.

Soil samples collected from the reference site and the runoff plots were analysed for ^{137}Cs activity at the Center for Nuclear Energy in Agriculture using an HPGE Coaxial Detector (GEM-20180P, PopTop) which provides a detection efficiency of 0.7% for the adopted geometry (1-l Marinelli beakers). The minimum detectable activity is of the order of 0.2 Bq kg^{-1}. Due to the very low ^{137}Cs activity of the soil samples and the very low detection efficiency, the counting time was extended to 24 h.

The ^{137}Cs activity of each experimental plot was evaluated through the average of the accumulated activities of the three soil profiles analysed for each plot. The quantification of ^{137}Cs loss (or gain) on each plot was made by comparison of the measured average inventory of the plot with the reference site inventory, according to:

$$Cs_{\text{Red}} = \left(\frac{Cs_p - Cs_{\text{Ref}}}{Cs_{\text{Ref}}} \right) 100 \qquad (1)$$

where Cs_{Red} is the percentage loss (erosion) or gain (deposition) of redistributed ^{137}Cs relative to the reference inventory, Cs_P (Bq m^{-2}) is the average total ^{137}Cs activity of each plot, and Cs_{Ref} (Bq m^{-2}) is the average total ^{137}Cs activity at the reference site. The conversion of Cs_{Red} (%) values into rates of soil erosion (or deposition), E (Mg ha^{-1} $year^{-1}$), was undertaken using the proportional model presented by Walling & He (1997).

RESULTS AND DISCUSSION

The ^{137}Cs inventories of the five soil profiles sampled at the reference site varied from 177 to 288 Bq m^{-2}, providing an average of 253 Bq m^{-2}, with a standard deviation of

46 Bq m^{-2} (*CV* = 18%). The 95% confidence interval for the mean is 221–285 Bq m^{-2}. Although the depth distributions of ^{137}Cs in the reference soil profiles showed evidence of some differences, on average more than 98% of the ^{137}Cs activity was present in the upper 20 cm of the soil.

According to the literature, in undisturbed soil profiles the highest concentrations of ^{137}Cs are generally found in the upper 20 or 25 cm soil layer (Basher *et al*., 1995). Therefore the results obtained for the five profiles analysed in the *Pueraria* field seem to be in accordance to what is expected for a reference site. Although the depth distribution of ^{137}Cs activity found in the soil profile seems to follow the decrease in the silt fraction of the soil with depth, no statistically significant correlation between both data sets was found.

In the case of the soil of the reference site that has maintained its cover of perennial legume for 60 years, the presence of ^{137}Cs at greater depths can be accounted for by vertical movement of soil particles caused by intense biological activity. The frequent occurrence of macropores left in the soil profile by the decomposition of old roots could be observed.

The mean total ^{137}Cs inventory for the three soil profiles (U, M and B) sampled in each erosion plot was converted into an erosion rate using the proportional model, taking the average total inventory of the five reference profiles (253 Bq m^{-2}) to represent the local ^{137}Cs reference inventory. The measured values of soil loss from each erosion plot were summed to cover the same period used for the calculation of erosion rates by the ^{137}Cs method (1963–2002). The erosion rates estimated using the ^{137}Cs method and the corresponding measured values for each plot are presented in Table 1.

According to the assumptions of the ^{137}Cs method, the values of ^{137}Cs gain (rather than loss) listed in Table 1 correspond to sediment deposition points. However, in most cases, except for position B of plot 8, the values are very low, and less than the standard deviation (46 Bq m^{-2}) of the mean ^{137}Cs activity for the reference site.

As can be seen in Fig. 1, a good correlation was found between the erosion rates estimated using the ^{137}Cs technique and the direct measurements. Kachanoski (1987), who compared ^{137}Cs losses and directly measured erosion rates for runoff plots in Canada, also observed a significant correlation. Although the ^{137}Cs activities found are very low when compared to those of the northern hemisphere, the ^{137}Cs technique can be seen to provide satisfactory estimates of erosion rates. However, when compared to the direct measurements, the erosion rate estimates provided by the ^{137}Cs technique appear to slightly overestimate the erosion rates.

As can be seen from Table 1, there is a tendency for higher ^{137}Cs inventories to be found in the soil profiles from the bottom third of the plots. In two of the eight analysed plots (5 and 8), inventories higher than the average value found in the reference area were observed, indicating possible sediment deposition. However, no statistically significant difference in ^{137}Cs inventories was found between the sampled slope positions. These higher inventories could be the result of the restriction to runoff caused by the presence of the permanent concrete plot borders. At the bottom part of the plots, the presence of the runoff collector system also represents a restriction to free runoff flow (Kachanoski, 1987) and could also explain the sediment deposition observed in this area.

Table 1 ^{137}Cs activity and erosion rates in the runoff plots.

	Sampling part of the erosion plot	^{137}Cs activity (Bq m^{-2})	^{137}Cs loss (Bq m^{-2})	^{137}Cs method (Mg ha^{-1} year^{-1})	Direct measurement (Mg ha^{-1} year^{-1})
1	U	50	–203		
	M	26	–227		
	B	52	–201		
	Average	43	–210	33	36
2	U	45	–208		
	M	43	–210		
	B	83	–170		
	Average	57	–196	42	39
3	U	68	–185		
	M	25	–228		
	B	77	–176		
	Average	57	–196	36	24
4	U	100	–153		
	M	56	–197		
	B	235	–18		
	Average	130	–123	22	20
5	U	107	–146		
	M	254	1		
	B	300	47		
	Average	220	–33	5	13
6	U	0	–253		
	M	0	–253		
	B	52	–201		
	Average	17	–236	39	43
7	U	260	7		
	M	273	20		
	B	270	17		
	Average	268	15	–4	11
8	U	149	–104		
	M	178	–75		
	B	430	177		
	Average	252	–1	–4	10

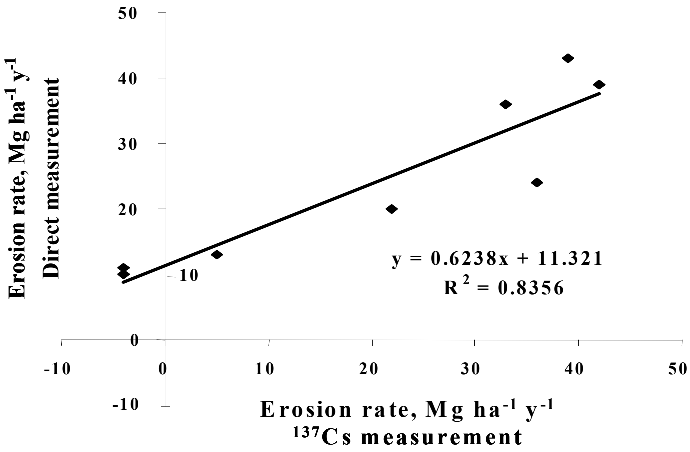

Fig. 1 Correlation between erosion rates obtained by direct measurement and the ^{137}Cs method.

The soil redistribution rates estimated using the ^{137}Cs technique reflect the integration of all landscape processes in the field. Thus, tillage erosion could also another reason for the higher ^{137}Cs inventories found in the bottom third of the plots. The erosion plots only provide information relating to the net soil loss from the area within the plot border measured by the collector system, and they are unable to provide information on the spatial pattern of erosion and deposition within the field. Equally, they do not permit the effects of tillage on sediment redistribution to be assessed (Walling, 1995). Since the estimates of soil loss provided by the ^{137}Cs technique relate to the individual sampling points, the spatial variability of sediment redistribution within the plots provides an additional cause of the differences observed between both procedures. The detailed spatial pattern of soil redistribution within the plots could be assessed using the ^{137}Cs technique, by employing a grid sampling procedure.

In conclusion, despite the very low ^{137}Cs activity in the soil, the ^{137}Cs technique yielded consistent results, comparable to those obtained by the traditional direct measurements on long-term runoff plots. The differences observed in the estimates of erosion rates can be attributed to limitations of both methods. The ^{137}Cs technique was able to highlight an important limitation of the direct measurements provided by erosion plots, relating to sediment deposition within the plot area.

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