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Soil erosion e valuation in a small watershed in Brazil through ^{137}Cs fallout redistribution analysis and con ventional models

O.O.S. BACCHI[(1)], K. REICHARD[(1, 2)], G. SPAROVEK[(3)] and S.B.L. RANIERI[(3)]

(1) Centro de Energia Nuclear na Agricultura - CENA/USP. Laboratório de Física do Solo Av. Centenário 303, CP.96, CEP- 13400-970 - Piracicaba,SP Brazil.

(2) Departamento de Ciências Exatas, Escola Superior de Agricultura "Luiz de Queiroz" ESALQ/USP

(3) Departamento de Solos e Nutrição de Plantas, Escola Superior de Agricultura "Luiz de Queiroz" ESALQ/USP Av. Pádua Dias, 11, CP 9, CEP 13.418-900- Piracicaba, SP, Brazil.

ABSTRACT

An investigation of rates and patterns of soil erosion on agricultural land cultivated with sugarcane was undertaken using the ^{137}Cs technique, USLE (Universal Soil Loss Equation) and WEPP (Water Erosion Prediction Project) model. The study was carried out on a representative catchment of a small watershed of the Piracicaba river basin, State of São Paulo, Brazil, called Ceveiro watershed, well known for its severe soil degradation caused by erosion. The results from the ^{137}Cs technique indicate that most part of the studied area (94%) are eroded at erosion rates that go up to 59 Mg ha^{-1}y^{-1}, with a weighted average rate of 23 Mg ha^{-1}y^{-1}. The weighted average rate of infield deposition and sediment retrieval that occurs in only 6% of the total area was estimated to be around 12 Mg ha^{-1}y^{-1}. These values led to very high net soil loss from the field, with rates of the order of 21 Mg ha^{-1} y^{-1}, which represents a sediment delivery ratio of 97%.

A linear correlation between soil erosion rate estimated by the ^{137}Cs technique and the amount of available K in the top soil layer (0-20 cm) was observed. Based on this correlation the estimated amounts of net and gross K loss in the grid area due to soil erosion were of 0.2 and 1.52 kg ha^{-1}y^{-1}, respectively. The erosion rate estimated by USLE was 39 Mg ha^{-1}y^{-1} and by WEPP model 16.5 Mg ha^{-1}y^{-1} with a sediment delivery of 12.4 Mg ha^{-1}y^{-1} (75%). The results are a confirmation that the soil conservation practices adopted in the area are very poor and can explain the high siltation level of water reservoirs in the watershed.

Key words: Soil erosion. Siltation. Cesium^{137}. USLE. WEPP.

RESUMO

O trabalho trata da avaliação da erosão hídrica em uma pequena microbacia cultivada com cana-de-açucar através da análise da redistribuição do "fallout" do ^{137}Cs, pela USLE (Universal Soil Loss Equation) e pelo modelo WEPP (Water Erosion Prediction Project). O estudo foi conduzido em uma microbacia representativa da bacia do ribeirão Ceveiro, pertencente à bacia do rio Piracicaba, Estado de

São Paulo, Brasil, bem conhecida pela severa degradação de seu solo por erosão. Os resultados do método do ^{137}Cs indicam que a maior parte da área estudada (94%) encontra-se severamente erodida, cujas taxas de erosão atingem valores de até 59 Mg ha^{-1} ano^{-1}, com uma média ponderada de cerca de 23 Mg ha^{-1} ano^{-1}. A taxa ponderada média de deposição de sedimentos dentro dos limites da área de estudo é estimada da ordem de 12 Mg ha^{-1} ano^{-1}, ocorrendo em apenas cerca de 6% da área total. Esses valores levam a uma taxa média líquida de perda de solo pela área como um todo da ordem de 21 Mg ha^{-1} ano^{-1}, o que resulta em uma razão de liberação de sedimentos de 97%, ou seja, quase a totalidade dos sedimentos mobilizados por erosão são transportados para fora dos limites da área de estudo.

Foi observada uma correlação linear entre as taxas de erosão estimadas pela técnica do ^{137}Cs e a concentração de K disponível na camada superficial do solo (0-20 cm). Baseada nessa correlação, as taxas líquida e bruta de perdas de K na área de estudo foram estimadas em 0,2 e 1,52 kg ha^{-1} ano^{-1}, respectivamente.

A taxa de erosão estimada pela USLE foi de 39 Mg ha^{-1}ano^{-1} e pelo modelo WEPP foi de 16,5 Mg ha^{-1}ano^{-1}, com uma taxa de liberação de sedimentos de 12,4 Mg ha^{-1}ano^{-1} (75%).Esses resultados são uma confirmação das inadequadas práticas conservacionistas adotadas na área e explicam o grande assoreamento observado nos reservatórios de água existentes na microbacia.

Palavras chave: Erosão hídrica. Sedimentação. Césio^{137}. USLE. WEPP.

INTRODUCTION

The Piracicaba river basin is a traditional sugarcane producing region of Brazil in which the crop had a large expansion of its old frontiers in the last 30 years. This large expansion of the sugarcane area was made mostly with the displacement of original pastures, annual crops, forests and reforestation areas. In many cases this expansion was achieved without an adequate evaluation of the land use capacity, thus exposing the new sugarcane fields to a high level of degradation risks. One example is the Ceveiro watershed, with an area of 2,200 ha, located at 22º40'S and 47º47'W, which belongs to the Piracicaba river basin. According to Sparovek et al. (1997), around 68% of its total area is now cultivated with sugarcane, 18% with forests and 14% with pastures. More than 80% of the land is classified in the range of IV to VIII by the land use capacity classification system (Sparovek, 1991). The high erodibility of the soils and the intense cultivation with sugarcane lead to high erosion rates which caused severe silting of a water reservoir, reducing its original volume to only 25%, and generating several sediment deposits within the watershed.

Visual signs or symptoms of the high rates of soil erosion and sediment delivery ratio from crop fields in the watershed are evident. There is however a need for a basic quantification of the rates and patterns of soil loss involved. The main reason for this lack of information is the unavailability of an adequate and cheap methodology for soil erosion and sediment delivery evaluation. Empirical and semi-empirical models present several well-known limitations for this purpose, mainly regarding sediment deposition and sediment delivery estimates. Other traditional direct methods like erosion pins, erosion frames and wash traps are generally short-term (intensive) and thus do not allow for a retrospective assessment of erosion rates.

The ^{137}Cs technique was applied in a wide range of environments in the north hemisphere, and a reasonably solid basis of the technique is established and well documented (Rogowski & Tamura, 1965, 1970; Ritchie & McHenry, 1990, 1995; Walling & Quine, 1993, 1995). Only a few basic measurements of ^{137}Cs activity in Brazilian soils are known. One reference is related to ^{137}Cs activity in soils from the north of Brazil (Sakai, 1977) at the Federal University of Bahia. In Piracicaba, SP, southern Brazil, few measurements were reported by Nascimento Filho et al. (1988) and Guimarães (1988). The activity found in 1988 by Nascimento Filho et al. (1988) in a watershed of the Piracicaba River Basin was of the order of 300 Bq m^{-2}. These values, around 10 times lower than the levels detected in some areas of the northern hemisphere, represent some difficulties for the use of this methodology and can be considered one of the main restrictions for its application in the region. The work in the Ceveiro watershed, reported here, provides an opportunity to examine the potential of the technique in these conditions, and at the same time allows the comparison of results generated by other methodologies.

STUDY AREA

The location of the study area and the topography of the sampling site are shown in Figures1 and 2. The topography of the Ceveiro watershed is characterized by presenting hills with altitudes ranging from 460 to 580 m and a rolling relief with average slopes ranging from 5 to

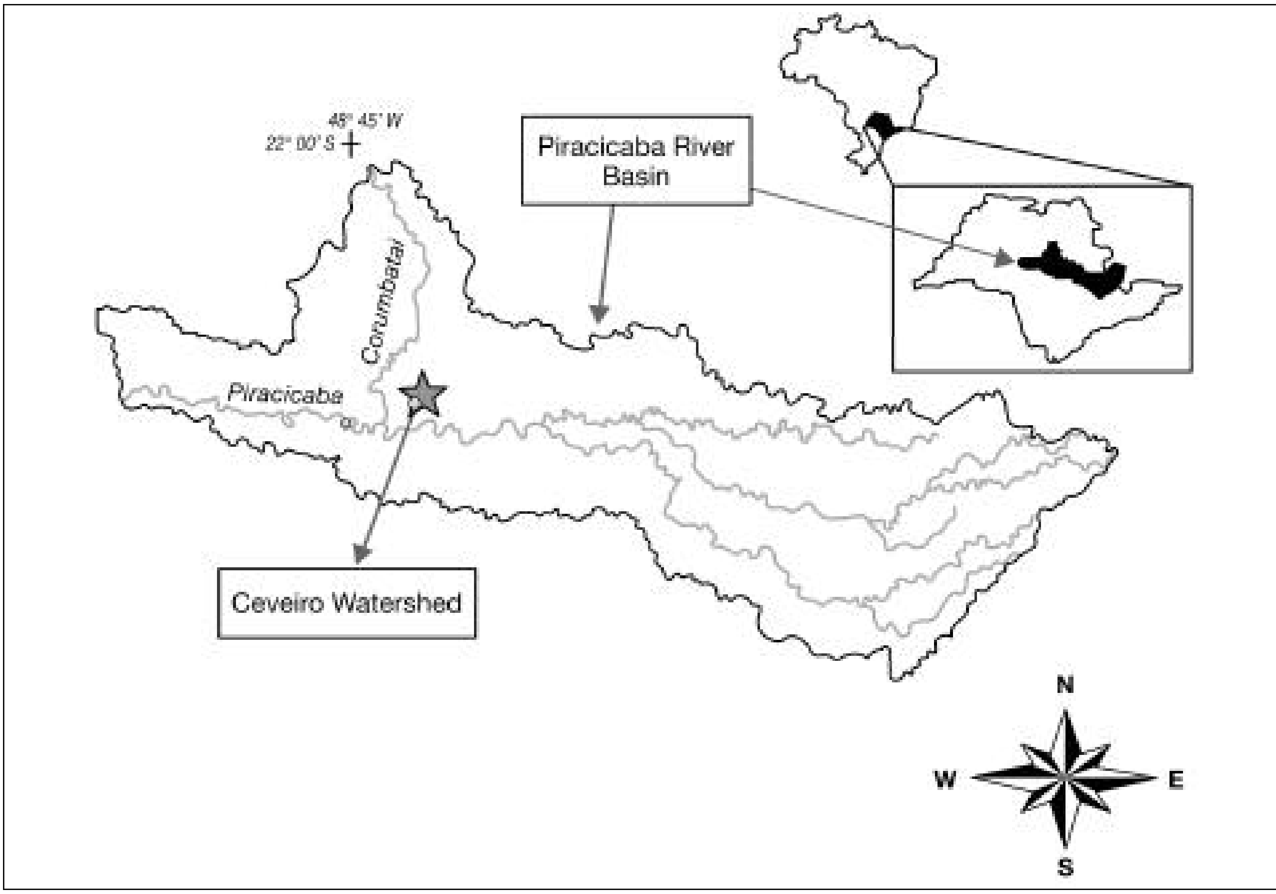


Figure 1. Location of the study site.

15%. Areas with slopes lower than 2% represent less than 5% of total area and are positioned at crests and footslopes. The sampling site was chosen to be representative of the general terrain of the area, extending over a full range of hillslope cycle, and it is fully occupied with the sugarcane crop.

The climate of the region is classified as Cwa according to Köppen's system, or humid sub-tropical, characterized by dry winter and temperatures higher than 22ºC during the warmest month. The summer is hot and rainy with a mean February temperature of 25ºC. The dry season covers the period from April to September with a precipitation of 278 mm, representing only 22% of the total annual precipitation (1254 mm). Land preparation for cane field renewal, which is made after each four or five ratoon cycle, is coincident with the dry season. However, the high precipitation intensities that occur during the first months of vegetative growth of the new planting cane exposes the land to a high erosion risk.

The main soil types of the watershed are classified as Arenic Paleudult, Arenic Abruptic Paleudult and Typic Dystrochrept. The high erodibility of these soils and the topographic characteristics of the watershed are the main restriction factors for the land use capacity.

Sugarcane has been cultivated in the studied area for more than 20 years, using the same conventional cultivation practices that are adopted at other lands less susceptible to erosion, without employment of any special soil conservation measures. Contour cultivation and terracing to divert runoff into natural drainage channels and then to lower levels of land are generally adopted. The natural waterways are however not well protected by vegetation or mechanical measures. Sugarcane producers of the region do not frequently adopt strip cropping and rotation strip cropping. Some farmers use the technique of dividing slopes by cane strips of different growth stages, in order to have a better soil protection. Despite the application of some beneficial practices, it is quite common to find signs of high erosion and deposition rates. One important symptom of the high sediment delivery from cropped land is the huge siltation observed in the water reservoirs of the watershed.

MATERIALS AND METHODS

The ^{137}Cs technique

The ^{137}Cs methodology was applied according to Walling & Quine (1993). The main procedures adopted were:

Sample collection: All samples were collected at sufficient depth in order to include all ^{137}Cs present in the soil profile.

Grid area - Bulk sampling was performed down to a depth of 80 cm using a 9.4 cm diameter hand cylindrical auger (Riverside auger). Three replicates for the following layers were taken from each grid point: 0-40 cm; 40-60 cm and 60-80 cm. The replicates from each layer were mixed in order to have a composite sample with enough soil volume to be analyzed.

Reference site - Depth incremental samples were taken down to a depth of 40 cm using a scraper hand tool, working inside a 30 cm diameter PVC cylinder, which takes a soil sample volume of 3,500 cm^3 in 5 cm thick layers (figure 3). This procedure proved to be advantageous in relation to the "scraper-plate" described by Walling & Quine (1993) when applied to sandy soils. The introduction of the PVC cylinder in the soil after scraping each 5 cm soil layer avoids next sample contamination by collapsed soil from upper sandy layers.

Sampling framework: Due to the non-uniform topography of the selected area, a grid framework was established consisting of 6 transects across the field. The distance between sampling points was approximately 30m. The coordinates of each sampling point were taken using a GPS with a precision of few centimeters.

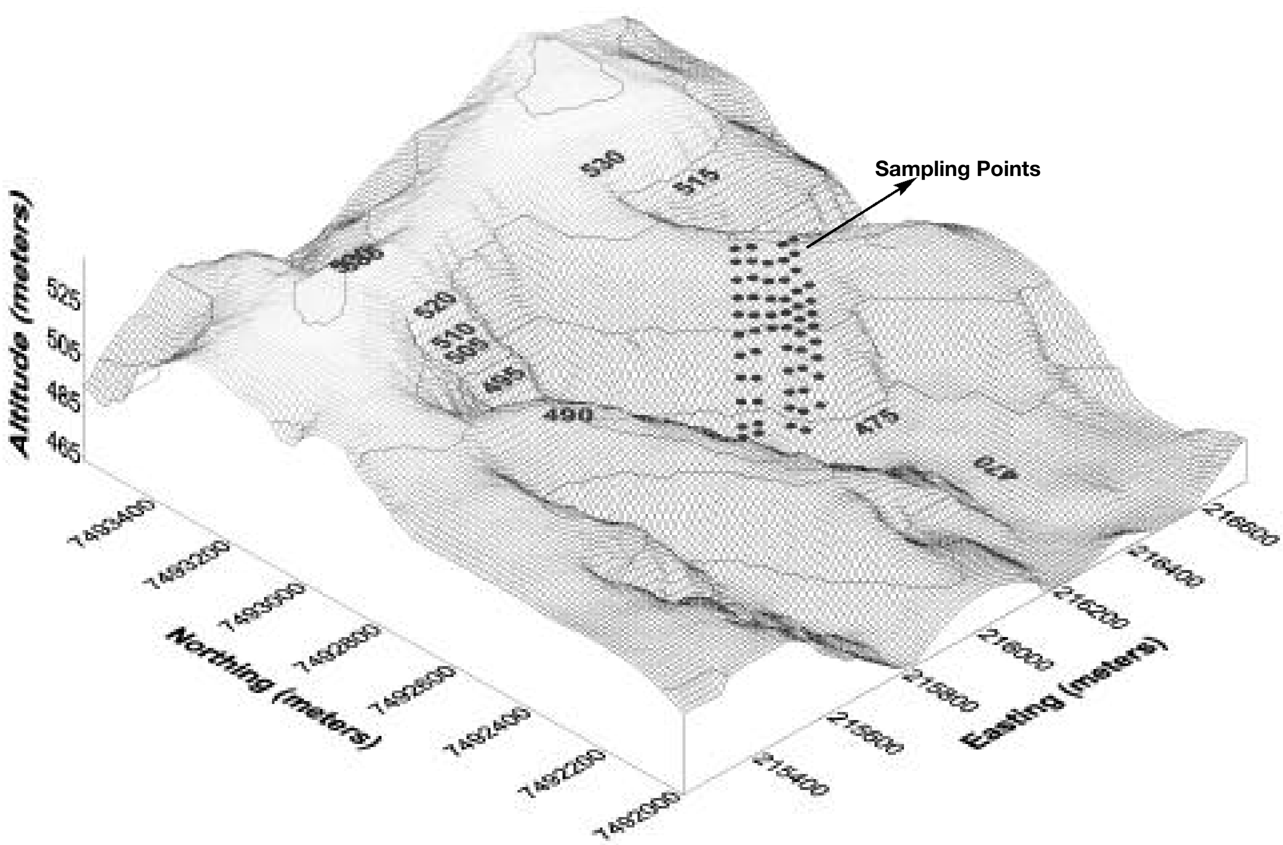


Figure 2. Topography of the study site and location of the sampling grid. (Coordinate system: UTM - Universal Transverse Mercator).

Table 1. Integrated grid area data.

Eroding sites	
Mean erosion rate (Mg $ha^{-1}y^{-1}$)	23.0
% of total area	94.1
Aggrading sites	
Mean deposition rate (Mg $ha^{-1}y^{-1}$)	12.1
% of total area	5.9
Whole field	
Gross erosion rate (Mg $ha^{-1}y^{-1}$)	21.6
Net erosion rate	20.9
Sediment delivery ratio %	96.7

Sample analysis:

^{137}Cs analysis - Gamma spectrometry equipment: Detector model GEM-20180P, Pop Top (EG & G ORTEC), associated to a multi-channel analyzer; 1 liter Marinelli Beakers. Counting time of 20-24hours.

Chemical and physical analysis - Soil samples taken from six depths (0-20, 20-40, 40-60, 60-80, 80-100 and 100-120 cm) of each point of the grid were analyzed for the most common physical and chemical properties such as: texture, pH, organic carbon, available nutrients, CEC and base saturation.

Estimation of erosion and deposition rates:

Conversion of ^{137}Cs inventories (Bq m^{-2}) into soil redistribution (Mg $ha^{-1}y^{-1}$) was made using the proportional model as described by Walling & He, (1997).

The USLE model - Universal Soil Loss Equation

USLE is an empirical erosion prediction model, described by equation 1 (Wischmeier & Smith ,1978).

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \quad (1)$$

where: A= soil loss per unit area; R= rainfall erosivity factor; K= soil erodibility factor; L= slope-length factor; S = slope-steepness factor; C=cover and management factor; P= support practice factor.

This model is largely used due to its relative few parameters. Nevertheless, USLE has some limitations when applied on non-uniform areas like a watershed and its direct application to whole transects still is a challenge when using GIS. Therefore, some adaptations were necessary to apply this model on the watershed.

First, it was necessary to generate climate, soil, topography and land use maps for the whole watershed. All of them were digitized using Autocad-12 Software (Censi et al, 1994). Each digitized map was then transformed in a raster format map using Geographic Information System (GIS) IDRISI (Eastman, 1992), with 20 X 20 m pixel, which contained the USLE parameters. The climate data for R factor calculation were obtained from a 30-year record of the Meteorological Station of Piracicaba. The soil data survey was derived from 89 sampling points, collected every 20 cm, in a 120 cm deep profile, which were analyzed for chemical and texture attributes. The K

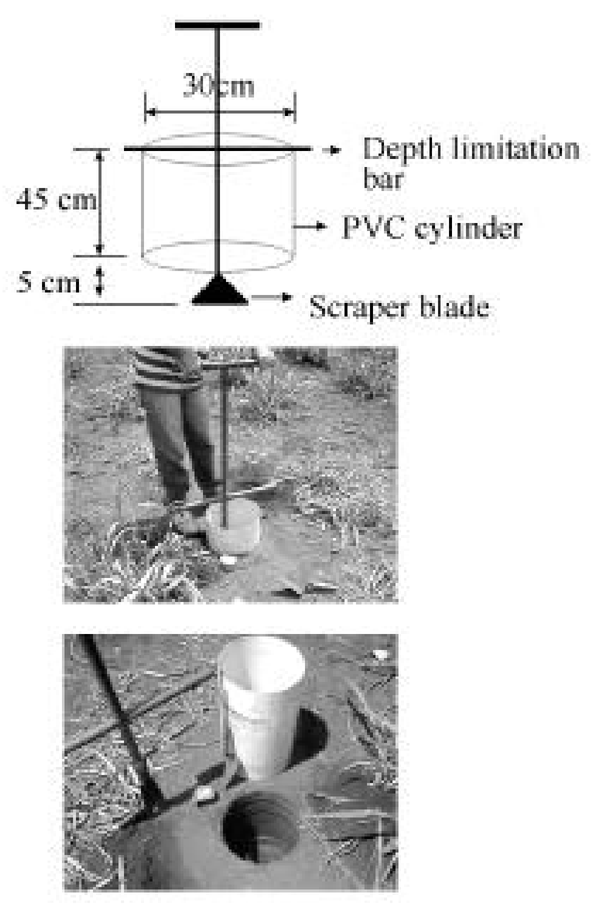


Figure 3. Sampling device for incremental depth samples

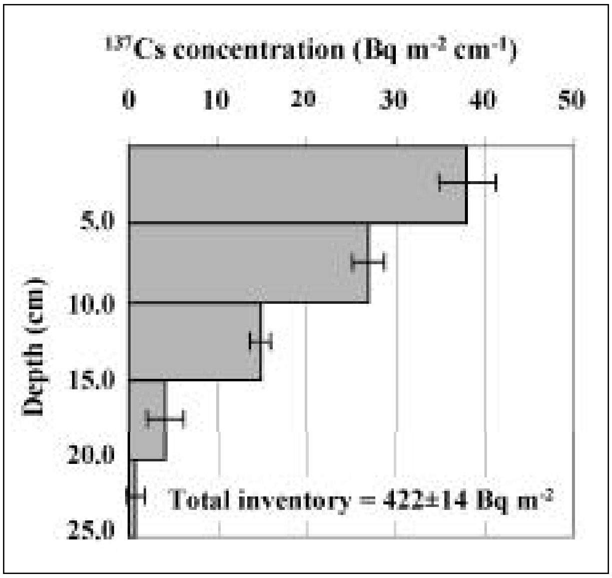


Figure 4. Average ^{137}Cs downward distribution at the reference sites.

factor was computed using the method described by Denardin (1990). Land use and management characterization were obtained based on aerial photographs of scale 1:25,000 and the C factor used for the sugarcane areas was the one proposed by De Maria et al. (1994). Topographic information was compiled from a 1:10,000 scale altitude contour map with vertical resolution of 5 m. Maps of homogeneous polygonal areas (same slope steepness and same slope azimuths) were generated from the slope and aspect maps, in order to allow the determination of the LS factor for slopes of similar characteristics of the studied transects of the grid area. The maps with the USLE parameters were overlaid in order to obtain the soil loss map for each homogeneous polygonal area with the same characteristics of the grid area.

The WEPP model - Water Erosion Pr ediction Project model

WEPP is a process-based model developed to compute soil loss, deposition and sediment delivery ratio on hillslopes or watershed scale (Flanagan & Nearing, 1995). Due to its complexity and to the need of a large number of input parameters, its use is still incipient in tropical environments. The use of a process-based model for erosion prediction is however, a new approach that needs investigation, mainly for areas with irregular relief and changes in soils and land use. Moreover, the WEPP model, in contrast to USLE, can estimate soil loss deriving from rill erosion.

The same sampling points used for USLE application were used for the WEPP model. These data included chemical, physical and hydrological parameters. The climate inputs were based on the same 30-year record. The plant and management inputs were obtained from the literature and from expert consultants. A WEPP-Hillslope version (Flanagan & Nearing, 1995) was used to estimate the soil loss from the studied area. The hillslopes were characterized using GIS vector format - MIPS®. Each hillslope with all soil and management information was exported from GIS to the WEPP-Hillslope model, in order to estimate soil loss, soil deposition and sediment yield.

RESULTS

^{137} Cs technique

Depth incremental samples collected at a flat pasture located 1 km far from the sample grid area were analyzed. The ^{137}Cs downward distributions at these sites evidenced a sharp decline in the radionuclide concentration. This allowed the acceptance of that profiles as undisturbed ones to be taken as reference points. The average reference inventory obtained from five profiles was estimated at 422±14 Bq m^{-2} and the average distribution of the ^{137}Cs concentration in the profiles is shown in Fig.4.

The spatial distribution of ^{137}Cs inventory at the grid sample area ranged from zero to 1,038 Bq m^{-2}. The analytical precision evaluated by the counting error of the peak area was estimated for each sample and varied from 3 to 20%. Erosion and deposition rates for each grid point were estimated using the proportional model proposed by Walling & He, (1997). Maximum estimated erosion rate was 59 Mg $ha^{-1}y^{-1}$ and maximum estimated deposition rate was 86 Mg $ha^{-1}y^{-1}$. Since the sampling grid spacing was constant, the integration of the grid data was made by interpolation, in order to estimate mean erosion and deposition rates, gross and net erosion rates and sediment delivery ratio. These estimated values are shown on Table 1.

The mean erosion and deposition rates are equal to the mass of soil eroded or deposited each year within the grid area, divided by the area under erosion or deposition, respectively. The gross erosion rate is equal to the mass of eroded soil each year within the grid area, divided by the whole grid area. The net erosion rate is equal to the difference between the mass of eroded and deposited soil within the grid area, divided by the whole grid area. The sediment delivery ratio is equal to the net rate divided by the gross rate, expressed in percentage.

Figure 5a shows the spatial pattern of soil redistribution rates, superimposed upon an isometric projection of the grid area topography. Interpolation and graphs were made using the software SURFER® (Golden Software).

As it can be seen from Table 1, most part (94.1%) of the grid area represents eroding sites, with a weighted average erosion rate of 23 Mg $ha^{-1}y^{-1}$. A more detailed data analysis indicates that 50% of the grid area looses soil at rates higher than 35 Mg $ha^{-1}y^{-1}$. The deposition area is limited to only 6% of the total area with a mean deposition rate of 12 Mg $ha^{-1}y^{-1}$. As visually expected due to water reservoir's severe siltation in the watershed, the sediment delivery ratio estimated for the grid area is very high (96.7%).

USLE and WEPP models

The average soil loss estimated by USLE for the studied area was 39 Mg $ha^{-1}y^{-1}$, 69.6% higher than the average result obtained by ^{137}Cs method, but close to its highest values. This value was higher than the tolerable soil loss values for the types of soils found in the studied area (Lombardi Neto & Bertoni, 1975). The USLE method did not permit the computation of sediment yield because it did not consider the deposition that occurs on complex hillslopes.

The average soil loss estimated by WEPP was 16.5 Mg $ha^{-1}y^{-1}$. It was 28.3% smaller than the average values obtained by ^{137}Cs technique. The values ranged from 1.9 to 21.5 Mg $ha^{-1}y^{-1}$, depending on the hillslope considered and its slope length and steepness. The average annual sediment yield estimated by WEPP model was 12.4 Mg $ha^{-1}y^{-1}$, ranging from 1.8 to 19.7 Mg $ha^{-1}y^{-1}$. This means that, from WEPP calculation, the average sediment delivery ratio is 75% for the studied area. This sediment yield is smaller than the results of ^{137}Cs method, indicating, however, a great sediment contribution to the streams. It is important to mention that the sediment delivery ratio estimates for some hillslopes was close to 100%, confirming the severe siltation of this watershed, as indicated by the Cs technique.

The spatial pattern of soil redistribution in the area and the high sediment delivery ratio show that the two terraces and other adopted conservation measures are not sufficient to protect the field.

Impacts of erosion on soil quality

Basic available soil physics and fertility data were also analyzed in order to assess the impacts of erosion on soil quality. One interesting observation was the correlation between soil erosion estimated by the ^{137}Cs technique and the amount of available K (resin extractable K) in the top soil layer (0-20cm), as it can be seen in Figure 5. The correlation can be explained by the fact that the grid area was not being cultivated for some years and therefore was not receiving K fertilizers for some period. If this were not the case a more uniform K distribution in the field would be expected.

The correlation found between the concentration of K ($mmol_c$ kg^{-1}) and estimated values of erosion/deposition E (Mg $ha^{-1}y^{-1}$) was:

$$K = 1.99+0.0117\cdot E \qquad (2)$$

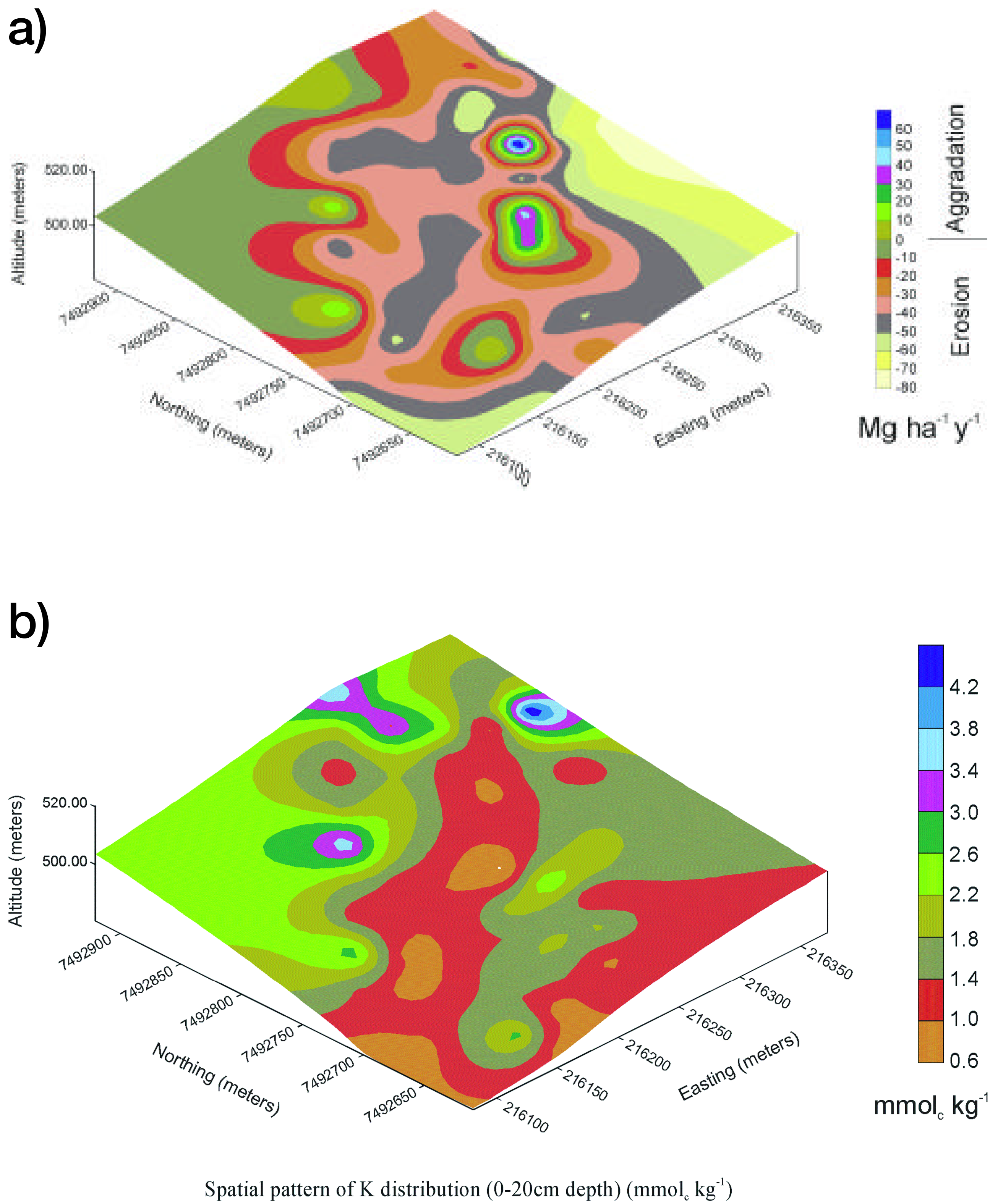
(regression significance level of F = 0.0024)

According to equation 2, for E=0 the average of K concentration at non-eroded points in the grid area is 1.99 $mmol_c$ kg^{-1}, which corresponds to 77.6 mg kg^{-1}. Considering the estimated net erosion rate of 20.9 Mg ha^{-1} y^{-1} for the whole field (E=-20.9) the correspondent concentration of K would be 68.07 mg kg^{-1}according to equation 1. Therefore, the difference in K concentrations for E=0 and E=-20.9 gives the amount of net K loss per kg of soil. The estimated value of net K loss for the estimated value of net erosion rate is 9.5 mg kg^{-1}. Multiplying the net loss of K (9.5 mg kg^{-1}) by the net erosion rate (20.9 Mg $ha^{-1}y^{-1}$) we have a net rate of K loss of 0.2 kg $ha^{-1}y^{-1}$. This value corresponds to an annual loss of 12% of the amount of the soil K parameter.

The concentration of K in the delivered sediment would be ranging from 77.6 mg kg^{-1} (E=0) to 68.07 mg kg^{-1} (E=20.9 Mg $ha^{-1}y^{-1}$) with an average of 72.8 mg kg^{-1}. Therefore, for a net erosion rate of 20.9 Mg $ha^{-1}y^{-1}$ a gross rate of K loss of 1.52 kg $ha^{-1}y^{-1}$ would be expected. The same order of magnitude of K losses was estimated by Tenberg et al. 1998 for one rainy season in southern Brazil.

CONCLUSION

The combination of soil, climatic and topographic conditions and inadequate soil conservation practices render the cultivated areas of the Ceveiro watershed very susceptible to erosion. The use of the ^{137}Cs technique as well as



Spatial pattern of K distribution (0-20cm depth) (mmol$_c$ kg^{-1})

Figure 5. a) Spatial pattern of soil redistribution rates superimposed upon an isometric projection of the grid area topography. b) Spatial pattern of soil and available K distribution within the grid area.

the USLE and WEPP models has confirmed that this susceptibility is reflected in high soil erosion rates. The ^{137}Cs technique allowed to map and to quantify the sediment deposition within the field and to generate previously unavailable estimates of sediment delivery. The very high sediment delivery ratio, of the order of 96%, is a confirmation that the soil conservation measures adopted in the area are not providing protection of the land as was suspected by the severe siltation of water reservoirs of the watershed.

In spite of the recognized limitations of the USLE and WEPP models when applied on non-uniform areas like a watershed using GIS, their results are in line with the estimates obtained through the ^{137}Cs technique.

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