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USE OF THE RADIOACTIVE ISOTOPE CESIUM-137 TO EVALUATE THE EROSION RATE ON A DEGRADED SLOPE IN MEXICO

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ABSTRACT

In the Ejido La Gavia, in the municipality of Almoloya de Juárez, State of Mexico, the soils dedicated to maize cultivation and cattle grazing show high levels of erosion. Therefore, it is convenient to estimate the soil erosion rate of crops in the sub-basin with the use of tracers. The hypothesis of this study was that the annual erosion rate (Mg ha^{-1} y^{-1}) on the degraded slope of the Ejido La Gavia can exceed the maximum permitted limits of erosion for this type of agricultural soils. The objective of this study was to quantify the annual erosion rate in a maize plot and a degraded slope of the Ejido, and to identify the deposit areas of the radioactive isotope Cesium-137 (^{137}Cs). The soil sampling of the degraded slope was made in four transects with ten samples in each one, obtaining a total of 40 soil samples. Five reference sites were included, out of which the ^{137}Cs profile was measured at 50 cm depth. At the reference site, the maximum value found was 6.8 Bq kg^{-1} at a depth of 10 cm, with 96 % of the ^{137}Cs content observed in the first 20 cm of the soil profile. The inventory of ^{137}Cs on the study slope was between 10.2 and 535.1 Bq m^{-2}, which was lower than that found in the selected reference site of 584.3 Bq m^{-2}. The mass balance model 2 was used, obtaining a soil loss rate with values of - 23.5, - 27.5, - 20.9, and - 22.0 Mg ha^{-1} y^{-1}. Soil erosion rates in the study four site transects far exceeded the permissible limit of 6.7 Mg ha^{-1} y^{-1}.

Keywords: erosion, soil degradation, radioactive isotopes, ^{137}Cs, deposition.

INTRODUCTION

In recent decades, the anthropogenic impact caused important changes in land use. The risk associated with the cycles of land abandonment and return to cultivation also implies certain threats to soil sustainability.

The study site is located within the Ejido La Gavia in the municipality of Almoloya de Juárez, State of Mexico. This Ejido is part of the physiographic province of the Trans-Mexican Volcanic Belt in Mexico, which is characterized by being an enormous mass of volcanic rocks of all compositions and formations with a variety of elevations, standing out among them Cerro La Guadalupana (3367 m, altitude) to the north, and

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Cerro San Antonio (3711 m, altitude) to the southwest of the municipality (SEDATU, 2016).

The total area of the municipality is 478.2 km^2, of which agricultural activity occupies an area of 309 km^2 (64.6 %). Of the total area, some 296.08 km^2 (96 %) are used for growing maize, which is found directly related to livestock activities that use an estimated area of 34 km^2 (7 %), and only 49.5 km^2 are for forest use (10.4 %). In the latter there are species such as pine, oyamel, oak and cedar, among others, with frequent clandestine logging and forest fires.

Soil erosion occupies 40.8 km^2, which represents 8.5 % of the municipal area. In 1991 the surface that presented this problem covered only 8.42 % of the municipal area, although for the year 2001 it increased to 12.58 %.

The type of rock is andesitic slab type, which is a rock formed of ash, lapilli and angular lava fragments, a combination of rock fragments and ash, formed by the torrential fall of rains on the deposits of unconsolidated fragmentary material (SEDATU, 2016).

The La Gavia sub-basin belongs to the Lerma-Santiago basin with a contribution area of 505 km^2, and is geographically located in the western part of the Lerma basin and on the border of the Balsas river basin, within the coordinates 19° 15′ and 19° 35′ N and 99° 40′ and 100° 00′ W. The degraded slope is located at coordinates 19° 24′ 7.5″ N and 99° 53′ 37.9″ W. In the La Gavia basin, erosion problems occur mainly in areas with rugged topography, where the slopes are steep.

There are plots where, over a period of 60 y, strata of up to 1 m of soil have been lost due to abandonment by the peasant owners, as a result of a reduced production and lower profitability of maize harvests.

The isotope ^{137}Cs is present in Mexican soils. In various studies of wild mushrooms from La Marquesa park, all the species collected and identified observed specific activity of ^{137}Cs in an interval between 3.6 and 646.5 Bq kg^{-1}.

Fungal species with high levels of accumulation and a higher percentage of ^{137}Cs are: *Gomphus floccosus*, with 152.2 Bq kg^{-1}, and *Clavariadelphus truncatus* with 96.9 Bq kg^{-1} (Valenzuela *et al*., 2004). Consequently, it is feasible to use them in Mexican soils as indicators of erosion-sedimentation processes.

Only physical processes that move soil particles, such as erosion and tillage practices, are involved in the movement of ^{137}Cs (La Manna *et al*., 2019).

The ^{137}Cs isotope, when it comes into contact with the soil, remains attached to organic matter and minerals, so that it moves with the soil during its transport (Gaspar *et al*., 2013). This means that the ^{137}Cs isotope is an effective tracer of soil movement in crop plots, so it is used to quantify soil erosion in fragile agroecosystems.

To calculate the annual erosion rate (Mg ha^{-1} y^{-1}) it is necessary to use mass balance models that use the ^{137}Cs inventory at a degraded slope study site compared to a reference site using the measurements of ^{137}Cs in the soil (Mabit *et al*., 2012; Walling *et al*., 2002).

Soil distribution is related to the presence and amount of ^{137}Cs measured at a reference site located on a hill with a flat surface that does not present erosion or sedimentation.

It is convenient that this site presents a surface covered with grass in a homogeneous way and be close to the study site or degraded slope (Fulajtar *et al*., 2017).

In the study site where the ^{137}Cs inventories are lower than the inventory of the reference sites, the loss of soil due to erosion processes can be inferred, and in the case that the measurement of ^{137}Cs in the study site is greater than the reference site value indicates that there is a sedimentation process.

The mass balance model (MBM 2) explains the changes of the ^{137}Cs contents in the reference soil profile over time. This is in response to precipitation of ^{137}Cs on the ground, losses of this tracer in the soil profile due to erosion, and incorporation of original soil that does not contain ^{137}Cs from the lower layers of the tillage depth, throughout the time when the precipitation of ^{137}Cs began until its maximum peak in 1963 (Gaspar and Navas, 2013; Fulajtar *et al*., 2017).

The solution of the mass balance equation provides the basis for establishing a relationship between the annual erosion rate due to soil loss and the percentage reduction of the ^{137}Cs inventory on the eroded slope under study, and the percentage reduction of the inventory of the reference site (Walling *et al*., 2002; Walling *et al*, 2014).

In this study, the results of the quantification of the temporal evolution of ^{137}Cs (Soto *et al*., 2002) in the soils of the reference site and the study site are used to estimate the annual erosion rate by means of the balance model of mass (MBM 2) adapted to the conditions of the site under study (Mabit *et al*., 2009).

In our view, the annual erosion rate (Mg ha^{-1} y^{-1}) on the degraded slope of the Ejido La Gavia exceeds the maximum permitted limits of erosion for this type of agricultural soils. Then, the objective of this study was to quantify the annual erosion rate in a maize plot and a degraded slope of this Ejido and to identify the ^{137}Cs deposition areas.

MATERIALS AND METHODS

Description of the study site and soil sampling

A slope representative of the agroecosystems of the Sierra Nevada was selected in the La Gavia sub-basin in the western part of the Lerma basin; to the west border limit with the Balsas river basin, in Mexico.

The relief is abrupt with an altitude between 2565 and 3600 m, and steep slopes with an average gradient of 19 %. The predominant climate is temperate subhumid, with an average annual temperature of 12 and 18 °C, rainfall in the driest month is less than 40 mm, with an average annual rainfall of 595 mm.

The predominant soils are Andosols, Vertisols and Feozems that border the Ignacio Ramírez reservoir. In general, most Andosols are found in the southeastern part of the basin; whereas the study area is on Vertisols (SEDESOL, 2010).

Four representative transects of the degraded slope were selected in order to represent the three different sequences located on the hill, slope and valley (Figure 1). The transects were established from the division of the hilltop at an altitude of 2498 m onto the flat land of the valley, located 2468 m before the La Gavia river. Lands are characterized by different altitude ranges and land uses. Forty surface soil samples

Figure 1. Location of the slope with the sampling points in four transects (circles) and the reference sites (squares) in the Ejido La Gavia, municipality of Almoloya de Juárez, State of Mexico.

were collected along the four transects separated by 25 m from each other using a global positioning system (GPS) (Gaspar and Navas, 2013).

The five reference soil samples were obtained by soil cores from undisturbed grass, located on the hilltop (19° 24′ 8.11′′ N and 99° 53′ 41.17′′ W) near the slope of the study site; and on the grass soil of the graveyard of the Community La Tinaja (19° 23′ 7.43′′ N and 99° 53′ 24.26″ W), with an area of 10 by 50 cm, with increments every 2 cm and a maximum depth of 50 cm.

Treatment and analysis of samples

Soil samples were air-dried, broken up by hand, and passed through a 2-mm sieve. The fraction greater than 2 mm corresponds to rock fragments and stones, which were separated from the fine fraction used for the ^{137}Cs analysis.

Soil properties such as texture, organic matter (MO) and pH were determined following the standard techniques described in NOM-021-RECNAT-2000. The MO content was measured by the ignition method at 500 °C. The pH (KCl 1M, solid-liquid ratio 1:2.5) was measured with a potentiometer, and the texture by the Bouyocus method.

The ^{137}Cs activities were measured using a 1.9 keV high resolution hyper-pure coaxial gamma ray detector for the energy of 661.6 keV and an efficiency of 30 %, with 10 cm thick lead shielding to reduce the natural background, coupled to a multichannel amplifier and analyser that was calibrated using standard certified samples in the same geometry as the study site samples (Navas *et al*., 2014). Each sample was measured for 30 000 s, producing results with an analysis precision of ± 6 - 8 % at the 95 % confidence level. The detection limit for ^{137}Cs was 0.1 Bq kg^{-1}.

The content of ^{137}Cs in soil samples is expressed as activity per mass (Bq kg^{-1}) and as cumulative activity or inventory (Bq m^{-2}), which is calculated using the mass of the soil sample in the fraction < 2 mm and the cross section of the sample.

Classical descriptive parameters including mean, minimum, maximum, range, coefficient of variation (CV), standard deviation (SD), and asymmetry were determined in Statgraphics Plus 5.1. The distribution of the variables was evaluated using the Kolmogorov-Smirnov test, and the Pearson correlation coefficients among the studied variables were determined using Statgraphics (Macedo *et al*., 2016).

RESULTS AND DISCUSSION

Statistical summary of the variables

The descriptive statistics of ^{137}Cs, organic matter (MO), pH, sand, clay and silt were calculated (Table 1). The selected parameters were normally distributed, as confirmed by the Kolmogorov-Smirnov test and the asymmetry values. The ^{137}Cs activity at the study site ranged from 10.2 to 859.8 Bq m^{-2}, with a mean value of 168.9 ± 167.7 Bq m^{-2}. The coefficient of variation of the activity of ^{137}Cs was 95, showing the distribution behaviour of ^{137}Cs by soil erosion in different degrees of affectation in the site, and deposition in few sampling points.

The highest and lowest CVs belonged to ^{137}Cs activity (99.3) and pH (11.4). The variability associated with these parameters depends on the irregular shape of the hill, the slope, the height difference between the degraded plot and the lower part of the study site. As well as the movement of water through erosion gullies in the central part of the slope, which leads to the redistribution of the soil in different parts of the landscape. The MO showed consistency in relation to the significant Pearson correlation coefficient with ^{137}Cs (Table 2). This relationship confirms that the amount of tracer depends on the content of organic compounds and silt present in the selected soils within the study site. The MO and pH are some indicators of soil quality and are identified as variables associated with soil redistribution.

It is likely that MO and silt distributions were influenced by the combined effects of agricultural practices, land use change, and erosion along the hillside. The CV

Table 1. Descriptive statistics for ^{137}Cs, organic matter (MO), sand, clay, silt, and pH (n=40) in soils of the Ejido La Gavia, municipality of Almoloya de Juárez, State of Mexico.

Variables	Unit	Means	DE	CV	Min	Max	Asymmetry
^{137}Cs	Bq m^{-2}	168.9	167.7	99.3	10.2	859.8	2.079
MO	%	7.4	2.5	33.9	3.30	15.6	0.976
Sand	%	61.7	7.5	12.1	47.08	77.8	-0.234
Clay	%	20.6	6.3	30.5	8.90	36.2	0.654
Silt	%	17.7	5.9	33.7	7.80	39.3	1.171
pH		4.2	0.5	11.4	3.45	6.1	1.250

N=40; MO: organic matter; DE: standard deviation; CV: variation coefficient; Min: minimum; Max: maximum.

Table 2. Pearson's correlation coefficient between the ^{137}Cs inventory and properties of the hill soils in the Ejido La Gavia, municipality of Almoloya de Juárez, State of Mexico.

	Unit	MO	Sand	Clay	Silt	pH
^{137}Cs	Bq m^{-2}	0.510¶	-0.100	-0.187	0.321†	-0.275
MO	%		-0.356†	0.137	0.297	-0.147
Sand	%			-0.638¶	-0.579¶	0.016
Clay	%				-0.258	-0.361†
Silt	%					-0.360†

†Correlation is significant at a (two-sided) $p \leq 0.05$, ¶Correlation is significant at a (two-sided) $p \leq 0.01$; Bold numbers mean a correlation coefficient > 0.5.
MO: organic matter; pH 1M KCl method.

values of the ^{137}Cs inventory and the properties of the selected soils are affected by the abandonment of the land due to the decrease in maize production and the erosion caused by the transit of livestock and sheep through the degraded slope. According to the classification criteria, the ^{137}Cs inventory was classified as highly variable (CV > 0.85); the MO, clay and silts were classified as moderately variable (0.15 < CV < 0.35); whereas the sand and pH were classified as slightly variable (CV < 15).

Depth increment profiles

The ^{137}Cs distribution profiles of reference sites 1 and 2 of grass soil located near the slope were consistent with those normally found in other reference sites (Tassano *et al*., 2021). Unlike sites of reference 3 and 4 of conserved grass soils that showed a tracer distribution different from references 1 and 2. The ^{137}Cs inventories decreased exponentially with soil depth. At sites 1 and 2 a peak in ^{137}Cs activity was observed within 6 to 8 cm of the soil; at reference site 1 the maximum value found was 7.9 Bq kg^{-1} at a depth of 6 cm; while at reference site 2 the maximum activity was 6.8 Bq kg^{-1} at a depth of 8 cm. Most (96 %) of the ^{137}Cs contents were observed in the 15 cm of the soil profile (Figure 2).

Beneath this there was an exponential decline in tracer activity (Du and Walling, 2011), with an inventory of 26.8 and 27.8 Bq kg^{-1}. In both profiles, the activity was not detected at a depth greater than 20 cm, so the ^{137}Cs was retained in the first twenty centimetres of soil by organic matter and clay. In references 3 and 4 of grass there was a peak at 2 cm on the soil surface; most of the content (95 %) was in the first 15 cm (Figure 3). The distribution of ^{137}Cs in the reference site 3 obtained in grass soil 10 m from a pine forest, presented the maximum value in the first 2 cm of soil with an activity of 10.2 Bq kg^{-1}, which is greater than reference site 4 with a maximum activity of 6.6 Bq kg^{-1} at the surface.

The inventory of the two reference sites 3 and 4 was 28.6 and 12.8 Bq kg^{-1}, respectively. An evident difference is observed in the inventory between reference sites 3 and 4, as

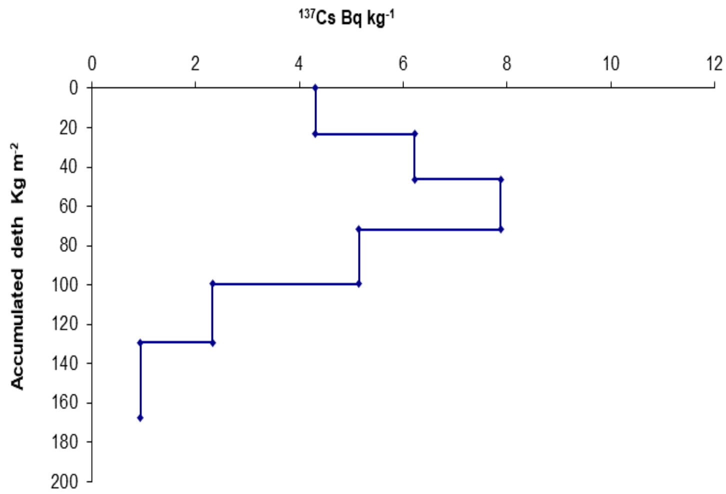

Figure 2. Distribution of the activity of ^{137}Cs in relation to the accumulated depth of the reference site 1 in the Ejido La Gavia, municipality of Almoloya de Juárez, State of Mexico.

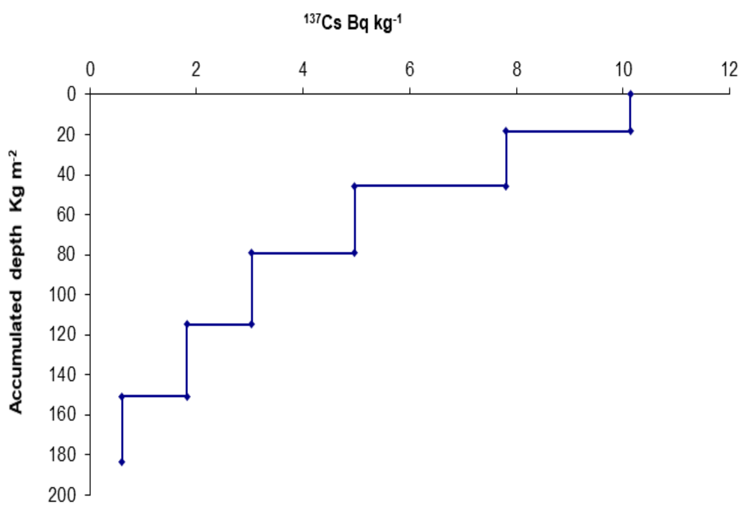

Figure 3. Distribution of ^{137}Cs activity in relation to the accumulated depth of reference site 3 in the Ejido La Gavia, municipality of Almoloya de Juárez, State of Mexico.

they underwent soil loss of the first centimetres during the sampling. The distribution of ^{137}Cs in the profile of reference site 7 showed an activity of 0.9 Bq kg^{-1} at the surface and increased to a maximum of 6.8 Bq kg^{-1} at a depth of 10 cm; then the activity diminished exponentially up to 20 cm deep, in which 92 % of the total inventory of 23.8 Bq kg^{-1} was found.

When comparing the distribution of ^{137}Cs in terms of mass depth, a difference is observed in the form between the five profiles of reference sites 1, 2, 3, 4 and 7, in which the inventory is different since the soils show different features. The results of ^{137}Cs in the reference sites and the soil mass analysed by area allowed calculating the accumulated depth (kg m^{-2}) and the activity in Bq kg^{-1} with which the distribution diagrams were constructed (Figures 2, 3 and 4). Reference site 1 showed a form of activity distribution based on the accumulated mass depth reported by other authors (Figure 2) (Velasco *et al*., 2018).

Reference site 3 presented greater activity in the first few centimetres of the soil surface. Although the shape of the distribution showed soil loss, probably due to cutting during the sampling process, or to the site was not representative of a reference site. (Figure 3).

The reference site 7 (Figure 4) showed a distribution similar to that reported in the literature. Due to the fact that the complete soil profile was sampled and obtained from the flat land located in the front of the graveyard of the Community La Tinaja; with soil not disturbed by tillage, construction or animal grazing.

The eroded slope was analysed in four transects T1, T2, T3 and T4. At each one, 10 measurements were obtained at different altitudes. Three of them were located on the upper slope of the site, six on the middle slope, and one on the valley, or plain. The ^{137}Cs inventory in the study plot ranged between 0.4 and 5.5 Bq kg^{-1} (10.2 and 535.1 Bq m^{-2}). The forty data were less than the inventory of 23.8 Bq kg^{-1} (584.3 Bq m^{-2}) of the selected reference site 7; which is an indicative of soil redistribution and transport from the hill to the plain of the study plot (Table 3).

Conversion model parameters

The tillage depth of 15 cm, bulk density of 1.2 kg m^{-3}, reference site 7 inventory of 584.3 Bq m^{-2}, a ratio factor of 0.42, were used as input to the MBM 2 model, as well as a relaxation depth of 4.2 kg m^{-2}, and a mass depth of tillage of 79.8 kg m^{-2}.

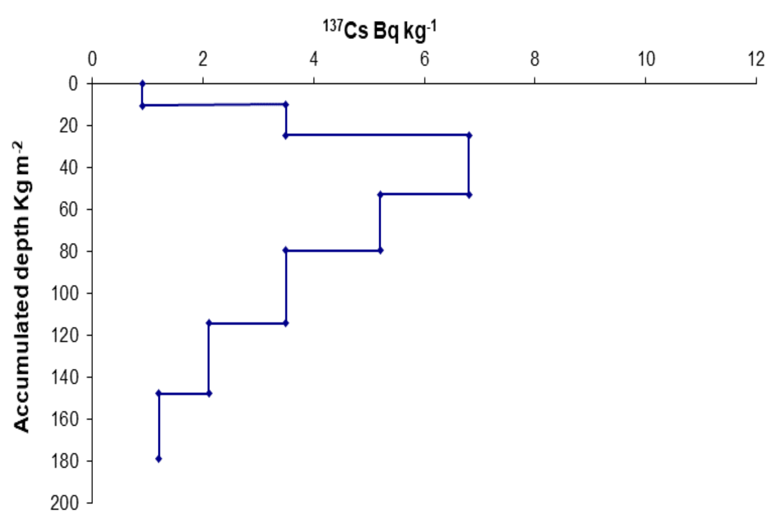

Figure 4. Distribution of ^{137}Cs activity in relation to the accumulated depth of reference site 7 in the La Gavia Ejido, municipality of Almoloya de Juárez, State of Mexico.

Table 3. Activity of ^{137}Cs in the soils of the study hillside in the four transects in the Ejido La Gavia, municipality of Almoloya de Juárez, State of Mexico.

T1		T2		T3		T4	
Bq kg^{-1}	DE	Bq kg^{-1}	DE	Bq kg^{-1}	DE	Bq kg^{-1}	DE
0.8	± 0.3	0.7	± 0.3	0.4	± 0.2	1.6	± 0.2
0.9	± 0.2	1.0	± 0.2	0.9	± 0.2	0.9	± 0.1
1.3	± 0.3	3.1	± 0.3	3.0	± 0.3	1.2	± 0.2
2.0	± 0.3	1.4	± 0.3	2.6	± 0.2	0.9	± 0.3
<0.1	-	<0.2	-	1.4	± 0.3	3.3	± 0.3
2.7	± 0.4	1.5	± 0.3	0.6	± 0.3	<0.1	-
0.7	± 0.1	0.4	± 0.1	1.0	± 0.2	<0.3	-
<0.1	-	<0.1	-	1.9	± 0.4	1.2	± 0.3
2.2	± 0.2	<0.2	-	<0.1	-	<0.3	-
1.4	± 0.3	1.0	± 0.2	1.0	± 0.3	5.5	± 0.4

DE: standard deviation.

The erosion rate (*R*) was calculated in the four transects of the study plot with the MBM 2 conversion model, which are expressed in units of Mg ha^{-1} y^{-1}. Results showed an interval between - 1.1 and - 54.3 Mg ha^{-1} y^{-1}, which indicates that erosive phenomena occur in the four transects studied, with the highest soil loss in transects 1 and 2 of - 23.5 and - 27.5 Mg ha^{-1} y^{-1}. Transects 3 and 4 resulted in negative values of - 20.9 and - 22.0 Mg ha^{-1} y^{-1}. Only one point located in the lowest part of transect 4 presented sedimentation (Figure 5) (Gil *et al.*, 2015). The average annual erosion rate of the four transects exceeded the permitted limit of 6.7 Mg ha^{-1} y^{-1} for this type of soils.

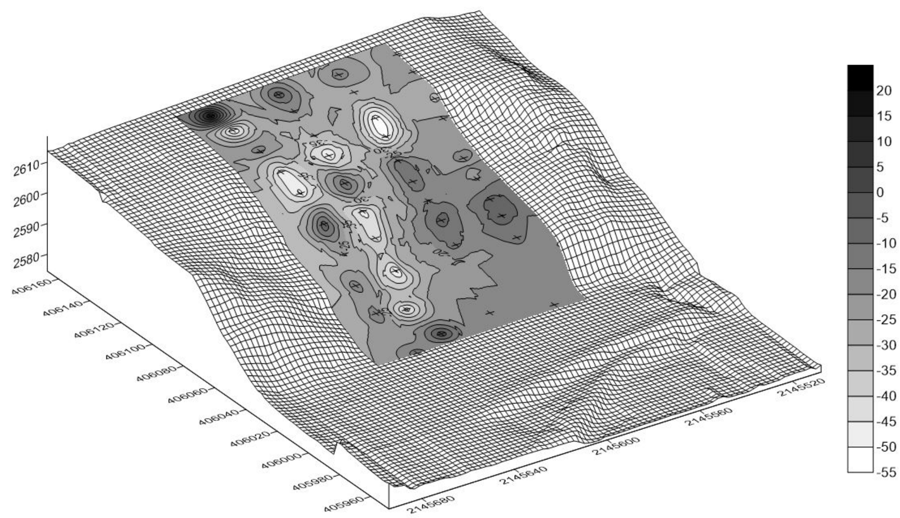

Figure 5. Annual erosion rate on the study slope in the four transects in Mg ha^{-1} y^{-1} in the Ejido La Gavia, municipality of Almoloya de Juárez, State of Mexico.

The soil eroding on top and slope moves to the lower lands of the plain at the study site, due to the force of the water runoff that causes the soil to move downwards. However, it was not deposited in the plain next to the study site. The activity of ^{137}Cs in the first 10 cm of site 5 of the study plain was less than the detection limit. A homogeneous profile was observed between 10 and 50 cm, with an activity that did not exceed 0.8 Bq kg^{-1} in this depth range. (Figure 6).

Between 50 and 60 cm, the activity of the tracer increased to 3.5 Bq kg^{-1}, although the inventory was lower than the reference site, so the processes that prevail in the plain near the hillside were erosive. The inventory of site 5 located in the plain (19° 24′ 8.11″ N and 99° 53′ 41.17″ W) is 12.4 Bq kg^{-1}, less than the inventory of the reference sites. Thus, the dominant process in this area is erosive and shows that the eroded soils were transported outside the study site, and there is a high probability that they would reach into the La Gavia river, which discharges downstream of the basin.

The results of the distribution of ^{137}Cs in the plot located in the lower part of the degraded slope showed the accumulation of sediments (Figure 6). This statement is confirmed when comparing the inventory of the reference site (23.8 Bq kg^{-1}) against the inventory of study site 6 (35.5 Bq kg^{-1}) of the plot located a few metres away from the La Gavia river. The maximum values were observed in the first 8 cm of the profile; then a decrease at 15 cm and another increase at 20 cm (Figure 7). The tracer distribution corresponds to removal from the lower soil layers to the upper ones, as they are displaced by the movement of the plough during the preparation of the plot land.

The inventory of site 6 of the plot was 35.5 Bq kg^{-1}, which is higher than the inventory of the reference site with 23.8 Bq kg^{-1}; thus, the dominant process in this area is deposition. The soils eroded from the hillside were accumulated in the plot near the La Gavia river in the Ejido La Gavia.

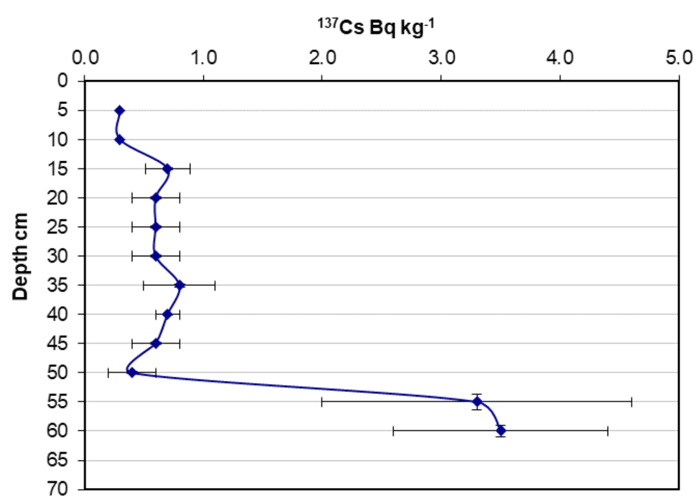

Figure 6. Distribution of ^{137}Cs in site 5 of the study plain in the Ejido La Gavia, municipality of Almoloya de Juárez, State of Mexico.

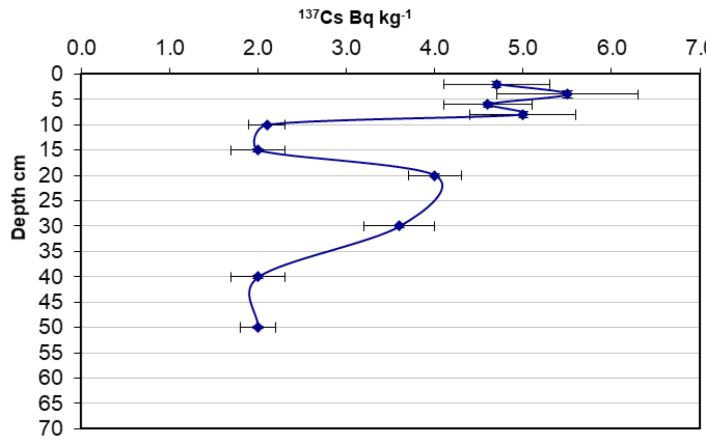

Figure 7. Distribution of ^{137}Cs in profile 6 of the plot of the study site in the Ejido La Gavia, municipality of Almoloya de Juárez, State of Mexico.

CONCLUSIONS

The weighted and retrospective erosion rates of the last 55 years exceed the permissible limit for these types of soils, by a 3-fold average value above such limit. Results indicated that the plot presents erosion in the hilltop, slope and in the plain, in which there is the accumulation of sediments in a single point of the plain.

The study with the tracer confirmed that the high levels of erosion generally observed on the slopes dedicated to livestock grazing, as well as to the cultivation of maize in central Mexico, makes it necessary to implement actions in order to reduce erosion and conserve the soil. Through the construction of terraces and reforestation with pines towards recovering the quality of the soils and the pine forests.

The study affirms the potential of using ^{137}Cs in Mexico to provide information on annual erosion rates and soil redistribution. The use of other tracers such as ^{7}Be and $^{210}Pbex$, among others, in the Ejido La Gavia would provide additional information on the soil erosion and sedimentation processes in the study area. They would be eventually useful to evaluate the effectiveness of practices of conservation to control and mitigate the degradation of Mexican soils.

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