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Study of ^{137}Cs redistribution in semi-arid land of western Algeria for soil loss assessment

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Abstract: Soil erosion is a global environmental problem, and anthropogenic fallout radionuclides offer a promising tool for describing and quantifying soil redistribution on decadal time scales. The ^{137}Cs technique for investigating rates and patterns of soil erosion has now been successfully applied in a wide range of environments. This radionuclide strongly adheres to soil particles and therefore can be used as a tracer in soil movement studies.

In this work we document the ^{137}Cs redistribution in an agricultural area, to assess the soil erosion and sedimentation zones. 77 samples were collected from the small Sidi Mohamed Cherif watershed extends over a surface area of 9.45 km^2 located in Oued Isser River in Northwest Algeria. The preparation of soil samples required drying, crushing and sieving to finally ≤ 2mm diameter.

The sample analysis was undertaken by gamma spectrometry, using a high resolution HPGe semi-conductor detector with (1.8 keV for ^{60}Co 1332.5 keV line), after soil characterization with Wavelength Dispersive X-Ray Fluorescence (WDXRF). The spectra were analyzed using the Genie 2000 software dedicated to the processing of gamma spectra. The specific activities of ^{137}Cs measured ranged from 0.37Bq kg^{-1} to 7.8Bq kg^{-1}. These ^{137}Cs measurements were used to estimate the spatial distribution of soil erosion in the study watershed.

***Keywords**: ^{137}Cs, Soil Characterization, Soil erosion, Gamma spectrometry, Northwestern Algeria.*

Introduction

The conservation of soil and water resources has become a major concern for ensuring global food production. Soil erosion and associated land degradation are major environmental problems encountered worldwide in the development of agriculture. Soil erosion and deposition cause not only on-site effects, but also off-site problems such as sediment deposition in fields, floodplains, and water bodies.

To control soil erosion, there is a need to monitor the impacts of land use and assess the effectiveness of specific soil conservation technologies (Walling *et al.*, 2014; Benmansour *et al.*, 2012; Mabit *et al.*, 2007, Rafiq *et al.*, 2011).

The use of radionuclide ^{137}Cs fallout provides an effective and valuable tool for the study of erosion and deposition in watersheds. ^{137}Cs technique has now been used to investigate soil erosion and redistribution in many areas in the world (Zapata. 2003; Edward *et al.*, 1994).

Algeria, like the Mediterranean countries, is actually affected by serious problems of land degradation due to water erosion and its effects. The main impact of water erosion is the reduction of soil fertility, which leads to the gradual disappearance of arable land, thereby causing sedimentation in water reservoirs. The mountain areas of North West Algeria are subject to fairly severe erosion due to a combination of physical factors and man. Despite all the efforts in this field, soil erosion continues at a frantic pace. Faced with this situation, there is a need for research concerning the processes of erosion current rates of soil loss and the impact of soil conservation techniques.

Many techniques were used to quantify and track soil erosion control and subsequently the development and degradation of natural environments, like conventional method based for USLE (Universal Soil Loss Equation) model. Soil loss estimated by this method need a measurement of many factors for all climates, soil types, topography, kinds of land and others factors. These several parameters make the technique heavy and expensive.

The limitation of conventional techniques for documenting soil erosion and redistribution rates have encouraged the development of Caesium-137 (^{137}Cs) technique to estimate erosion. This environmental radionuclide is currently widely used as a tracer for documenting soil redistribution in watersheds (Ritchie *et al.*, 1974). There are many environmental radionuclides, but only a few can be used to trace the movement of soil and sediment particles. Caesium-137 has several advantages in this context, including its mode of introduction into the environment, its affinity for sediment particles, and its half-life (Ritchie and McHenry, 1990; Longmore *et al.*, 1983; Edward *et al.*, 1994).

Caesium-137 is a man-made radionuclide produced by the atmospheric testing of thermonuclear weapons during the period extending from the mid-1950s to the early 1960s. The radiocaesium was released into the stratosphere and globally distributed. Global fallout of ^{137}Cs began in 1954, peaked in the early 1960s and subsequently decreased, reaching low levels in the mid-1980s. Fallout levels were globally variable, reflecting both annual precipitation amount and location relative to the main weapons tests (Walling, 2002).

Caesium-137 has a half-life 30.17 years. Absence of any natural source of ^{137}Cs in the environment, its strong and rapid adsorption to soil particles and its relatively long half-life makes ^{137}Cs a good tracer for soil erosion and sedimentation studies. ^{137}Cs fallout reaching the soil surface with precipitation is rapidly and strongly adsorbed by fine sediment particles and binds readily to the < 2 mm fraction of the soil. Its subsequent mobility is limited and loss the environment during harvesting is negligible, its subsequent redistribution directly reflects the mobilization, transport and deposition of soil particles by erosion (Bachhuber *et al.*, 1982; Walling and Quine, 1993). There is a close relationship between the loss or gain of ^{137}Cs at a sampling point and the rate of erosion or deposition, respectively. This relationship is used to estimate soil erosion and redistribution rates.

Estimation of erosion and deposition rates is based on comparing the ^{137}Cs inventory at a given location with that of a nearby 'reference' location (Walling and Quine 1990b). The reference site is selected to represent an undisturbed site where neither erosion nor deposition will have occurred during and since the period of fallout. The fallout of ^{137}Cs can commonly be assumed to have been essentially uniform over a field or small watershed. A loss or gain in the ^{137}Cs inventory at a sampling point when compared with the inventory at the reference site can be attributed to erosion or deposition, respectively. Comparison of measured inventories at individual sampling points with the local reference values provide useful qualitative information on the spatial distribution of erosion and deposition in the landscape. Quantitative estimates of erosion and deposition rates at sampling points can be derived from the measured loss or gain in ^{137}Cs inventory at the sampling point, relative to the local reference inventory, using a range of conversion models (Walling *et al.*, 2002; 2011).

The key advantage of this technique is that it provides retrospective information on medium-term (50-60 years) erosion/deposition rates and spatial patterns of soil redistribution without the need for long-term monitoring program. This study described in this report was undertaken to test the application of the ^{137}Cs technique in Algeria and to provide a preliminary assessment of soil erosion and redistribution rates in a small catchment in northwestern Algeria.

This study is devoted to the first estimate of the spatial distribution of ^{137}Cs inventories in the soils of a small watershed located within the Oued Isser river basin near Tlemcen in northwestern Algeria, to assess spatial distribution of the erosion and sedimentation within the small watershed and to provide estimates of the erosion and deposition rates within the small catchment to target and promote efficient soil conservation practices.

77 soil samples were collected from the study catchment. The soil samples processed and their ^{137}Cs activity was measured by gamma spectrometry in the laboratory. The activity concentrations were used to delimit erosion and accumulation zones and to produce estimates of the erosion and deposition rates involved.

Materials and methods

Sampling and sample preparation

The study area is located approximately 40 km east of the city of Tlemcen in Northwestern Algeria (see Figure 1a).The main study site was a small 945 ha, watershed known as Sidi Mohamed Cherif located at an elevation of 350 to 500 m above sea level, with a slope gradient up to 20 %. The study catchment is a small tributary of the Oued Isser. The mean annual temperature is 18°C, with monthly mean temperatures ranging from 1°C in January to 35°C in June. The mean annual precipitation for the Watershed is approximately 300 mm, with annual totals ranging from 200 to 400 mm. Approximately two thirds of the rainfall occurs during period October to March, when irregular torrential storms occur rainfall. The study watershed is characterized by marly lithology, highly dissected a very steep topography steep slopes and a high drainage density. Conventional tillage at depth less than 30 cm, was practiced over a long period in this field. The soil pH is neutral or slightly basic. Soil organic carbon (SOC) content varied from 0.75 to 2.7% and decreasing with the depth (0.6 to 1%). The C/N ratio (10 to12) shows a good evolution of the organic matter. Nitrogen and assimilable phosphorus are deficient. Soils are deeply reworked and frequently impoverished by erosion. (Morsli *et al.*, 2005). All these factors favor water erosion processes.

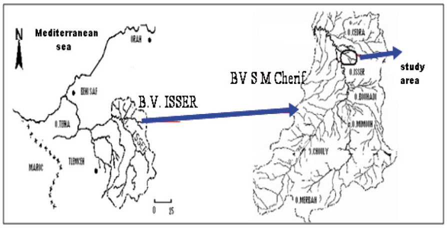


Figure 1a: Views of the Study area
Figure 1b: Views of the cultivated field and Wischmeier Plot

77 soil samples were collected manually from the study area. 70 of these samples were collected from 10 points along two parallel transect within the small watershed, the distance between these transects was 10 m (see Figure 1b). These sampling points $P_{n,m}$ (*n*: transect number and *m* point number), were selected to be representative of the topography, and the distance between two adjacent points was 20 m. Depth profiles comprising six samples were collected from each of the ten sampling points. A further depth profile was collected from a forested reference site (Pr) located 1 km outside the experimental site; the reference site was selected so they met the following

criteria:

a. undisturbed since the beginning of the 1960s;

b. not influenced by the erosive processes, which imply a plane topography.

The depth profiles obtained from each sampling point were collected from 40 x 40 x 40 cm soil pits, the individual samples were taken from depths of 0-5, 5-10, 10-15, 15-20, 20-25, 25-30 and 30-40 cm with hollow steel cube of 625 cm^3 volume, they internal dimensions were 25 cm long, 5 cm large and 5 cm high (Mabit *et al.*, 2007). The samples were stored in plastic bags labeled according to the depth, and were transported in the laboratory. Details concerning the topography of the study site and the sampling points are presented in Figure 2.

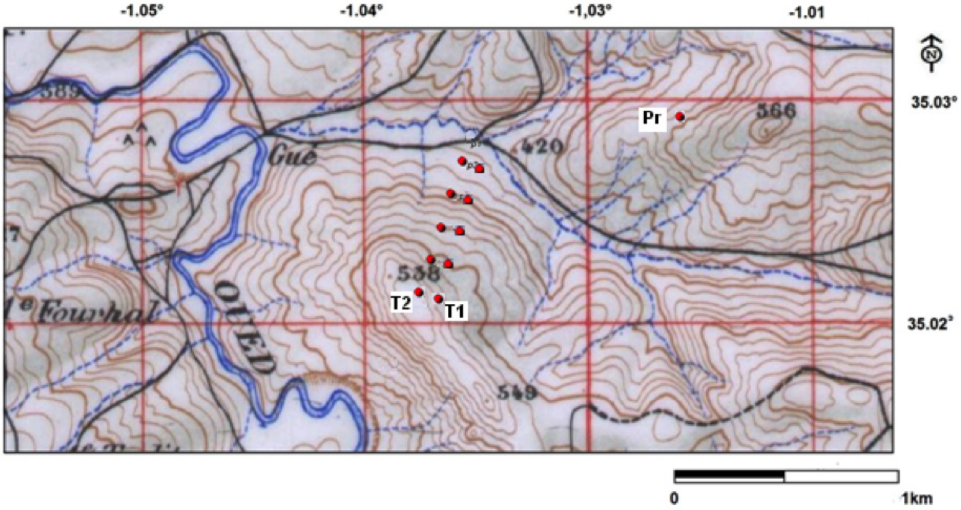


Figure 2 - Topography of the study site and sampling design.

After return to the laboratory, the soil samples were air dried, after further drying in an oven at 105°C for 48 hours, the samples were disaggregated and sieved to separate the < 2 mm fraction. After homogenization, a representative of the < 2 mm fraction comprising 500 g was loaded into Marinelli beaker for determination its ^{137}Cs activity concentration by gamma spectrometry. The bulk density of soil was determined at the laboratory, by the ratio of dry mass to volume; the mean value of bulk density was between 1.15 g cm^{-3} at the surface and 1.5 g cm^{-3} in depth.

Soil geochemical properties

Small quantities of representative soil were analyzed using the Wavelength Dispersive X-Ray Fluorescence (WD-XRF) method to determine their geochemical properties and clay composition.

The WD-XRF spectrometer used in this work was a Magix Pro (Panalytical ex Philips) equipped with an X-ray tube with a Rhodium anode, and a series of eight crystal analyzers covering the analytical range of elements from boron to uranium. It is also equipped with three detectors used for X- ray measurements: the first one is a gas flow counter, the second one is a proportional counter sealed xenon and the third one is a scintillation detector used for high energy X-ray measurements.

An 8 grams aliquot of soil was pelletized using a hydraulic press in order to irradiate it for analysis. The samples are irradiated with primary X-rays produced by the X-ray tube. To improve the signal to noise and obtain good resolution, X-ray filtration is carried out by a series of collimators (150, 550 and 4000 microns) used in three wavelength regions; short, medium and long wavelengths (Magix Pro, Panalytical, system user guide). X-rays emitted characteristic of sampled elements are then separated by crystal analyzers on the principle of Bragg diffraction. The collection and spectra analysis are undertaken using Super Q software, provided by Philips. Qualitative analysis of spectra is performed on the basis of a comparison of the angular positions of the experimental peaks compared to a database that includes all of the trace elements.

The peak intensity of identified elements was converted to a quantitative analysis through a calibration curve prepared using standard samples. The representative soil composition of is given in Table 1.

Radiometric measurements

The ^{137}Cs activity of the content of the ≤ 2 mm fraction of each sample was measured using a gamma spectrometry technique composed of High Purity Germanium (HPGe), with a carbon-epoxy entrance window manufactured by CANBERRA, used for routine gamma spectrometric analysis in the environmental laboratory. The detector had the following specifications: 35% relative efficiency, 1.85 keV resolution (FWHM) at 1332.5 keV and 0.86 keV at 122 keV. The Desktop Spectrum Analyzer DSA 1000 was used in this work to process the gamma spectra of the soil samples. The detector was surrounded with 114 mm-thick graded lead shield (Canberra 747 Series Lead Shield), with liners of 3 mm of tin and 1.5 mm of copper to reduce the contribution to the spectrum of the lead X-rays, achieving a low background needed in low activities measurement applications. The calibration of the detection system was performed using Monte Carlo method validated with certified ^{152}Eu sources (Azbouche *et al.*, 2015).

All samples were counted for 86400 seconds to obtain good counting statistics, and the measurement errors were less than 5%, this step is necessary to identify and determine the activity concentration of ^{137}Cs in the samples. The spectrum treatments were carried out using the Genie2000 software.

Table 1 - Representative soil composition of studied watershed.

Sample	Bulk density (g cm^{-3})	Composition	Concentration (%)
Soil	1.25	Na_2O	0,045 ± 0.003
		MgO	2.378 ± 0.01
		Al_2O_3	16.38 ± 0.50
		SiO_2	51.05 ± 0.80
		P_2O_5	0,136 ± 0.009
		SO_3	0.092 ± 0.004
		K_2O	2.902 ± 0.02
		CaO	16.763 ± 0.06
		TiO_2	0.97 ± 0.16
		MnO	0.076 ± 0.004
		Fe_2O_3	7.33 ± 0.30

The activity concentration, A_s (Bq kg^{-1}), of the ^{137}Cs in the soil was determined as:

$$A_s = \frac{N}{e\, P\, t_c f m} \qquad (1)$$

Where N is the net area at the interest peak energy at 661.6 keV of ^{137}Cs, corrected for background counts, e is the detector efficiency at 661.6 keV gamma ray energy determined by Monte Carlo simulation, m is the sample weight in kg, t_c is the collection time in second, f is the self-attenuation of gamma rays in the sample and P is the gamma ray emission probability.

Results and discussion

The activity concentrations of ^{137}Cs measured in the soil profiles collected from the study watershed and the reference site are presented in the Tables 2 and 3.

The minimum detectable activity (MDA) of ^{137}Cs under these experimental conditions were 0.3 Bq kg^{-1}. This measured value was used to verify that the measurements of ^{137}Cs in the soil layers under 30 cm depth are less than MDA and also to confirm that all quantity of ^{137}Cs soil was used in soil erosion assessment.

Table 2 - Activity concentrations of ^{137}Cs (Bq kg^{-1}) in the soil profiles collected from transect1 and the reference site.

Depth (cm)	P_r	$P_{1,1}$	$P_{1,2}$	$P_{1,3}$	$P_{1,4}$	$P_{1,5}$
0-5	7.80±0.51	3.63± 0.22	4.51±0.24	5.36±0.33	4.93±0. 31	6.57±0. 42
5-10	4.69±0.29	3.10 ± 0.19	4.23±0.24	4.35±0.27	4.33±0.30	6.44±0.41
10-15	3.48±0.21	2.61 ± 0.16	3.01±0.16	3.45±0.21	3.88±0.25	6.87±0.45
15-20	2.14±0.13	2.32 ± 0.13	3.09±0.19	3.41±0.20	3.89±0.25	7.47±0.51
20-25	1.48±0.11	2.39 ± 0.14	2.05±0.12	2.96±0.17	1.15±0.09	5.39±0.34
25-30	0.81±0.09	0.41 ± 0.06	1.23±0.10	1.06±0.09	0.37±0.06	4.57±0.29
30-40	0.37±0.08	< MDA	< MDA	< MDA	< MDA	0.45 ± 0.1

Table 3 - Activity concentrations of ^{137}Cs (Bq kg^{-1}) in the soil profiles collected from transect2.

Depth (cm)	$P_{2,1}$	$P_{2,2}$	$P_{2,3}$	$P_{2,4}$	$P_{2,5}$
0-5	3.13± 0.21	4.45±0.32	5.01±0.35	4.61±0.32	6.35±0.44
5-10	3.15 ± 0.22	4.33±0.30	4.99±0.25	4.03±0.28	6.74±0.47
10-15	3.61 ± 0.25	3.91±0.27	3.96±0.27	3.18±0.21	7.05±0.49
15-20	2.92 ± 0.20	3.89±0.27	3.98±0.28	3.99±0.27	7.31±0.51
20-25	2.29 ± 0.16	2.65±0.18	2.98±0.21	3.15±0.21	5.49±0.38
25-30	0.43 ± 0.06	1.20±0.11	1.11±0.11	0.53±0.06	4.07±0.28
30-40	< MDA	< MDA	< MDA	< MDA	0.4 ± 0.1

The activity concentrations (Bq kg^{-1} dry weight) of ^{137}Cs in the depth-incremental samples collected from the different sampling points varied between 0.37 Bq kg^{-1} at depth in study site, and 7.80 Bq kg^{-1} at the surface in reference site. Most effective adsorption property belong to clay fraction of the soil (Cremers *et al.*, 1988), the highest level of ^{137}Cs is associated with clay fraction of the soil, which was analyzed by WD-XRF (see Table 1).

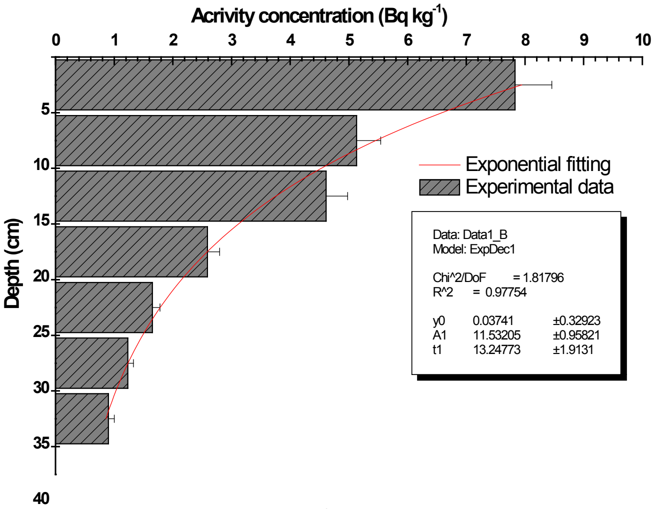
Tables 2 indicates that the highest levels of ^{137}Cs activity concentration were observed in the soil samples collected from point Pr (reference site). This conforms to expectations; at this site the activity concentrations also show the exponential decrease with depth which is an expected of an undisturbed reference site. The lowest ^{37}Cs activity concentrations associated with the surface samples from the depth incremental profiles were obtained from the sampling points

$P_{1,1}$ and $P_{1,2}$. The depth distributions of ^{137}Cs activity concentrations for the ten sampling points within the study watershed provide a basis for distinguishing between eroding and depositional sites. For the profiles $P_{1,1}$ and $P_{2,1}$, the activity concentrations are low. This can be linked to progressive loss of soil from the surface by erosion and dilution of the activity within the tillage layer by incorporation of soil from deeper in the profile containing no or only very low levels of ^{137}Cs.

On the Figure 3, we give some profiles of the ^{137}Cs depth distribution at eroded and deposition zones along transects slopes. This figure presents the average ^{137}Cs depth distributions at other sampling points within the study watershed. These have been grouped into eroding and depositional sites along the slopes transects.

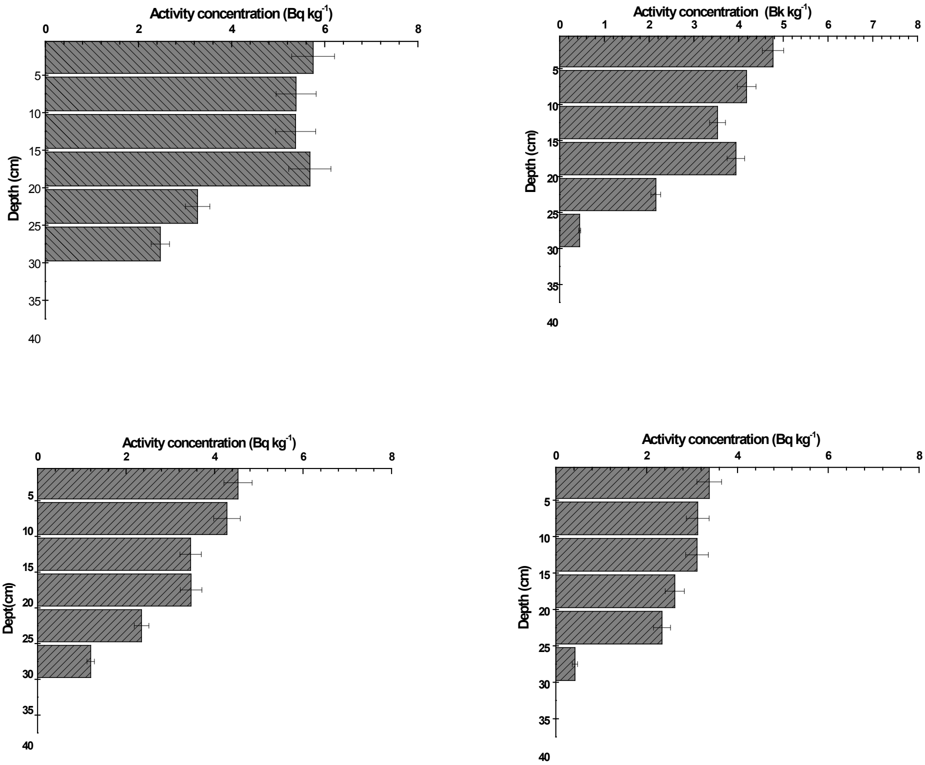
The numbers of points used to identify the different profiles in Table 2 and 3 are indicated. The ^{137}Cs profiles associated with four sampling points along the transect down the cultivated slope (from $P_{1,1}$ to $P_{1,4}$ and from $P_{2,1}$ to $P_{2,4}$) are characterized by reduced ^{137}Cs activities relative to the reference site (Pr), indicating that they are erosion zones. These points are characterized by rapidly decreasing inventories with depth and the radioisotope is found less than 30 cm deep.

Profiles $P_{1,5}$ and $P_{2,5}$, collected from the bottom of the slope is characterized by relatively high ^{137}Cs activities both near the surface and at depth. The ^{137}Cs activity concentration exceeds 4 Bq kg^{-1} at a depth of 25-30 cm under the tillage depth. These features and the limited variation of ^{137}Cs activity concentrations with depth indicate that this profile was collected from a deposition zone.

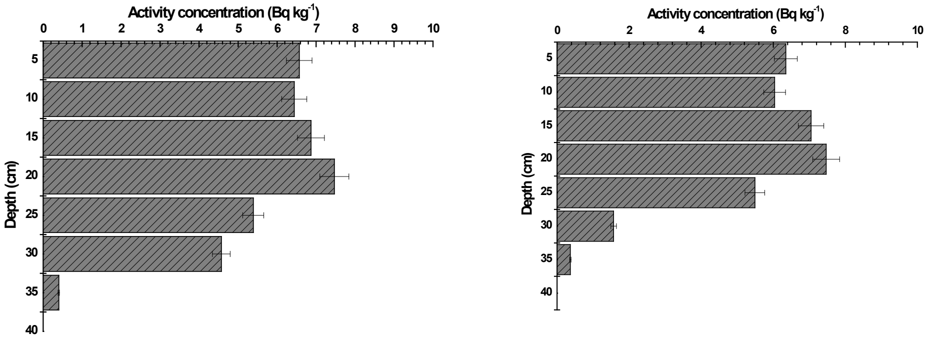


Reference site

Figure 3 - Average vertical distribution of ^{137}Cs activity (Bq kg–1) associated with the reference site and eroding and depositional zones along the slope transect within the study watershed.



Erosion zone



Accumulation zone

Figure 3 - Continued

^{137}Cs inventories

To estimate the soil redistribution rates along the transect, the ^{137}Cs activity concentration values obtained (Bq kg^{-1}) for the individual depth incremental sections of the profiles were used to establish the ^{137}Cs are al activity density or inventory (Bq m^{-2}) associated with each profile using the relation:

$$A(\text{Bq m}^{-2}) = \frac{(\sum \text{Weight (kg)}*A(\text{Bq kg}^{-1})}{\text{Section (m}^2)} \qquad (2)$$

For the whole of points studied, the concentration of ^{137}Cs inventory ranged from 300 ± 56 Bq m^{-2} to 789 Bq m^{-2}. The mean value of ^{137}Cs inventories measured for the reference site was 490 ± 126 Bq m^{-2} (mean ± CV). The ^{137}Cs activities of the soil collected in the erosion zones were lower than the reference inventory and for accumulation zone was higher.

For soil loss assessment, the ^{137}Cs specific activities need to be converted into soil movement using conversion models. The proportional and simplified mass balance models (Walling and He, 1997; Zapata, 2003) were used to estimate the soil erosion rates associated with the sampled points.

Proportional model

The proportional model was applied in the first estimation, this model require only information on plough depth in addition to values of ^{137}Cs for sampling point. The proportional model equation is given by:

$$y = \frac{(100\ TP)}{10\ \ BdX} \qquad (3)$$

Where Y is mean annual soil loss (t ha^{-1}yr^{-1}); d is depth of plough or cultivation layer (m); B is bulk density of soil (kg m^{-3}); X is percentage reduction in total ^{137}Cs inventory (defined as $[(A_{ref}-A)/A_{ref}]$x100; T is Time elapsed since initiation of ^{137}Cs accumulation (yr) and P is particle size correction factor, taken equal 1in this work. This model is easy to use. However, the assumptions of this model are a considerable oversimplification of reality in terms of the accumulation of ^{137}Cs in the soil. The accumulation of ^{137}Cs takes place over several years and some of the fallout input will remain at the soil surface prior to incorporation into the soil profile by cultivation. If some of the ^{137}Cs accumulated on the surface is removed by erosion prior to incorporation into the profile the estimates of soil loss provided by the model will overestimate actual rates of soil loss (see Table 4).

Simplified mass balance model

The mass balance model I (the simplified mass balance model) for cultivated soils described by Zhang *et al.*, (1990) was used to obtain the second estimates of erosion rates. The erosion rate can calculated as:

$$Y = \frac{10dB}{P} \ln\left[1 - \left(1 - \frac{X}{100}\right)^{1/(t-1963)}\right] \qquad (4)$$

The soil erosion and deposition rate measured in each point with proportional and mass balance models is given in the Table 4.

Table 4 - Erosion and deposition rates of study site measured estimated by proportional model (PM) and simplified mass balance model (SMB).

Transect number	Sampling point	Cs-137 inventory Bq m^{-2}	Soil loss (PM) (t ha^{-1} yr^{-1})	Soil loss (SMB) (t ha^{-1} yr^{-1})	Observation
T1	P1,1	300 ± 52	-19.6	-16.0	Erosion
	P1,2	376 ± 66	-11.7	-8.4	Erosion
	P1,3	428 ± 84	-6,3	-4,2	Erosion
	P1,4	386 ± 68	-10.7	-7.6	Erosion
	P1,5	783 ± 116	30.6	22.7	Deposition
T2	P2,1	323 ± 55	-17.3	-13.5	Erosion
	P2,2	424 ± 83	-6.7	-4.5	Erosion
	P2,3	458 ± 87	-3.2	-2.1	Erosion
	P2,4	405 ± 81	-8.7	-6.1	Erosion
	P2,5	769 ± 109	29.2	21.9	Deposition

The simplified mass balance model takes into account the progressive reduction in the ^{137}Cs concentration of the soil within the plough layer due to the incorporation of soil containing negligible ^{137}Cs from below the original plough depth and thus represents an improvement over the simple proportional model. This model is also easy to use and requires only information on plough depth. However, it does not take into account the possible removal of freshly deposited ^{137}Cs fallout before its incorporation into the plough layer by cultivation, which may occur during rainfall events which produce surface runoff and therefore erosion (Zhang *et al*, 1999). As a result it may overestimate the erosion rate. The average rate gross soil erosion and net erosion were estimated to be ca 12 t ha^{-1} yr^{-1} and 4.9 t ha^{-1} yr^{-1} respectively; this value can be compared with equivalent estimates for agricultural areas in the southern Mediterranean agricultural region (Benmansour *et al.*, 2013).

Conclusion

^{137}Cs measurements have been successfully used to estimate soil erosion rates along a transect down a cultivated slope within a steeply sloping small watershed in a semi arid area of Northwestern Algeria. The study demonstrates that ^{137}Cs measurements provide and quick and relatively inexpensive technique for evaluating medium-term (i.e. ca. 55-60 years) soil loss. The preliminary results confirm the significance of soil erosion in northern Algeria and demonstrate considerable potential for using the ^{137}Cs technique for further soil erosion and redistribution studies in the region.

The proportional and simplified mass balance models were used in this work; the simplified mass balance model gave a reasonable estimate, considering many factors influence the redistribution of fallout ^{137}Cs in landscape. Soil texture, slope and land use influenced the magnitude of erosion. The results obtained at the field should be useful in determining the appropriate land and water management, and will be compared with classical techniques of soil erosion measurement. Due to this first study on the cultivated soil, the further research should be conducted, involving the prediction of erosion and transportation rate in the whole catchment, so that we can estimate the quantity of soil nutrients and mechanism of soil quality evolution.

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