USING CONVERSION MODELS TO ESTIMATE SOIL EROSION AND DEPOSITION RATES, FROM THE ^{137}CS MEASUREMENTS IN CULTIVATED SOILS (NORTH MOROCCO)

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Resumen: En este estudio se utilizan técnicas de ^{137}Cs para determinar la erosión del suelo en cultivos de la vertiente de El Hachef (N de Marruecos). Se han tomado 35 muestras de 40 cm. de profundidad en suelos cultivados y 3 en suelos naturales. La erosión del suelo y velocidad de sedimentación han sido estimados utilizando 3 modelos de conversión: proporcional (PM), de balance de masas simplificado (MBM1), y de balance de masas estandard (MBM2). La relación media erosión/sedimentación mediante PM fue 14/16, con MBM1 32/37 y con MBM2 29/32 t ha^{-1} año^{-1}. Además, se seleccionó una pequeña franja para identificar la contribución de la labranza en la redistribución de ^{137}Cs utilizando el modelo de balanza de masas 3, utilizando un muestreo de transecto. Se observa que la redistribución de ^{137}Cs está controlada por la erosión del agua.

Palabras clave: Cesio-137, velocidad de erosión, modelos de conversión, Norte de Marruecos.

Abstract: This study is aimed to use the ^{137}Cs technique to determine the soil erosion on cultivated land in El Hachef watershed (north of Morocco). Thirty-five cultivated sites and three undisturbed sites were sampled to 40 cm depth. The soil erosion and deposition rates were estimated by using three conversion models: the proportional model (PM), the simplified mass balance model (MBM1) and the standard mass balance model (MBM2). The mean erosion/deposition rate estimated with the PM were 14/16, 32/37 with MBM1 and 29/32 t ha^{-1} yr^{-1} with MBM2. In addition, a small representative field was selected to identify the contribution of tillage on the ^{137}Cs redistribution by using the mass balance model 3, the sampling strategy was based on a transect approach. It is observed from the results that the pattern of ^{137}Cs redistribution is dominated by water erosion and that the contribution of tillage redistribution remains low.

Key words: Cesium-137, erosion rate, conversion models, North Morocco.

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Soil erosion is a natural process that is influenced by human activities. Indeed, over-cultivation and physical disturbance can decrease or increase soil erodibility by changing surface roughness, burying plant materials, or leading the soil more erodible immediately after tillage. In North Morocco, soil management is probably one of the main cause of soil degradation. In that case, estimation of erosion rates and assessment of the major factors influencing this erosion are necessary to propose conservation programs and planning.

Many methods have been used to measure soil erosion rates, like the quantification of the sediment transported by runoff wash and rills or the survey of ground elevation changes (Roose, 1991). The ^{137}Cs technique is now the commonly used method for estimating soil erosion rates on agricultural land. This is due to the high affinity of ^{137}Cs for fine particles, its half-life ($T_{1/2}$ = 30,2 years) adapted to the quantification of erosion over the last decades and its easiness of measurement. The potential of this technique has been widely recognized in many studies around the world (Walling and Quine 1990; Walling *et al.*, 1995; He and Walling 1997; IAEA 1998; Bernard *et al.*, 1998; Sogon 1999) and in Morrocco (Bouhlassa *et al.*, 1994; Moukhchane, 1999; Bouhlassa *et al.*, 2000; Benmansour *et al.*, 2000; Radakovitch *et al.*, 2002; Ibrahimi *et al.*, 2003; Nouira *et al.*, 2003; Damnati *et al.*, 2003).

The first objective of this work is to estimate erosion rates on a large cultivated area using ^{137}Cs measurements and conversion models described by Walling and He (2001): the proportional model (PM), the simplified mass balance model (MBM1) and the standard mass balance model (MBM2). The second objective is to study the variation of ^{137}Cs inventories along slope transects on a cultivated field and the pattern of the erosion rates.

Study area and Methodology

The study area is the «El Hachef» catchment (222 km^2) located 30 km south of Tangier (north Morocco) and feeding an artificial reservoir created in 1996 (**Fig**. 1.a). Soils basin are brown soils on stone wares and vertisols developed on the marly soft cliff. Climate is Mediterraneen type sub-humid and annual average precipitation is about 800 mm.

Sampling was undertaken from November 1999 to September 2001 in marly cultivated soils of the catchment area. 35 cores were collected along cultivated slope transects. One cultivated field (0.5 ha) was also selected to specifically study the variation along the slope between two transects (Fig. 1b). The position of the sampling points were estimated by using a GPS system.

Soils were collected from the surface until 30 or 40 cm depth and sectioned into 2, 5 or 10 cm increments. They were air-dried, passed through a 2 mm sieve and weighted. The ^{137}Cs content of the < 2 mm fraction of each sample was measured by gamma spectrometry (energy at 662 Kev) on a hyperpure coaxial germanium detector (CEREGE laboratory). ^{137}Cs activities (Bq/kg) measured for each increment were converted into total soil inventories (Bq/m^2) using the total weight of the bulked core sample and the cross sectional area of the sampling device.

The basic principles of the ^{137}Cs-technique used in this study have been established by Walling and Quine (1993). To derive quantitative estimates of the rates of soil erosion and deposition from ^{137}Cs measurements in the studied cultivated transects, the proportional model (PM), the simplified mass balance model (MBM1) and the standard mass balance model (MBM2), from Walling and He (2001) and Walling and Quine (1990) have been used.

Hypotheses of the proportional model are that ^{137}Cs is mixed homogeneously in the ploughed horizon and soil loss is directly proportional to the reduction of the ^{137}Cs inventory relative to the local reference. The mean annual soil loss rate Y (t ha^{-1} yr^{-1}) is:

$$Y = 10\frac{BdX}{100TP}$$

(1)

where X is the percentage reduction in total ^{137}Cs inventory (defined as $100*(A_{ref}-A)/A_{ref}$); d the depth of plough or cultivation layer (m); B the bulk density of soil (kg m^{-3}); T the time elapsed since initiation of ^{137}Cs accumulation (yr); A_{ref} the local ^{137}Cs reference inventory (Bq m^{-2}); A the total ^{137}Cs inventory at the sampling point (Bq m^{-2}) and P a particle size correction factor.

The second model used is the simplified mass balance model MBM1 which assumes that the total ^{137}Cs fallout occurred in 1963 (when the fallout reached the maximum intensity) instead of extending from the mid 1950s to the mid 1970s (Zhang *et al*., 1990). Thus, the depth distribution of ^{137}Cs in the soil profile is not time dependent. According to this model, the mean annual soil loss rate Y (t ha^{-1} yr^{-1}) is:

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

(2)

Deposition rates R¢ is estimated from the ^{137}Cs concentration in deposited sediment:

$$R' = \frac{A_{ex}(t)}{\int_{1963}^{t} C_d(t')e^{-\lambda(t-t')}dt'} = \frac{A(t)-A_{ref}}{\int_{1963}^{t} C_d(t')e^{-\lambda(t-t')}dt'}$$

(3)

where t is the time since 1963; $A_{ex}(t)$ the excess ^{137}Cs inventory of the sampling point ($A - A_{ref}$) at year t (Bq m^{-2}); C_d(t¢) the ^{137}Cs concentration of deposited sediment at year t¢ (Bq kg^{-1}) and l the decay constant of ^{137}Cs.

In the second version of mass balance model (MBM2), the variation of total ^{137}Cs inventory A(t) (Bq m^{-2}) for a point experiencing erosion, is expressed as follows:

$$\frac{dA(t)}{dt} = (1-\Gamma)I(t) - (\lambda + P\frac{R}{d})A(t)$$

(4)

On a deposition site, the deposition rate R¢ is calculated from:

$$R' = \frac{A_{ex}}{\int_{t_0}^{t} C_d(t')e^{-\lambda(t-t')}dt'}$$

(5)

where R and R¢ are the erosion and deposition rate (kg m^{-2} yr^{-1}) respectively; d the cumulative mass depth representing the average plough depth (kg m^{-2}); I(t) the annual ^{137}Cs deposition flux (Bq m^{-2} yr^{-1}); G the percentage of the freshly deposited ^{137}Cs fallout removed by erosion before being mixed into the plough layer. G can be expressed as $\Gamma = P\gamma(1-e^{-R/H})$ where g is the proportion of the annual ^{137}Cs input susceptible to removal by erosion, and H (kg m^{-2}) is the relaxation mass depth of the initial distribution of fallout ^{137}Cs in the soil profile.

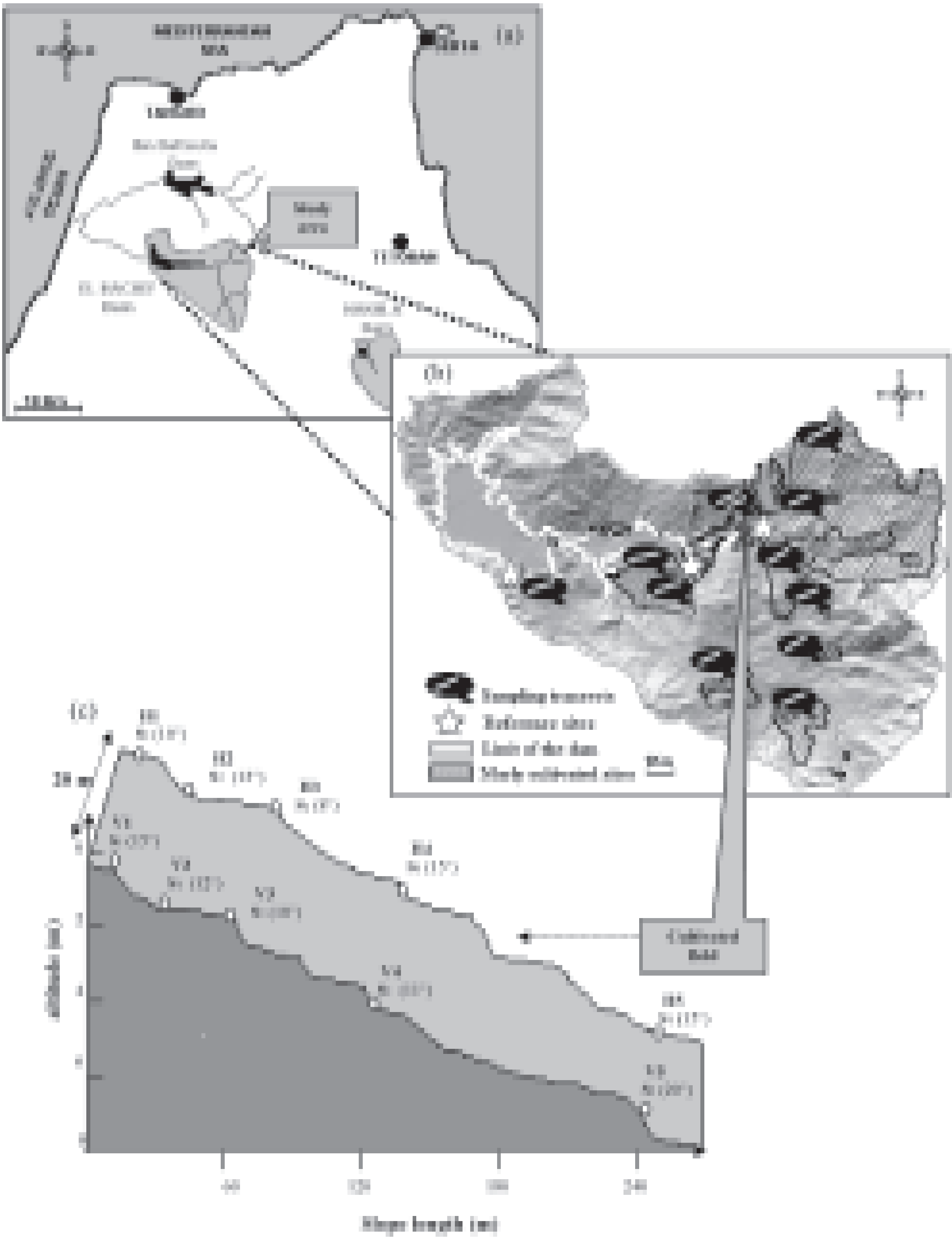

Figure 1.- El Hahchef catchment location **(a)**, sampling transects in the study area **(b)** and the two slope profiles **(c)** collected on the cultivated field (S=slope in degrees).

In addition to the three models cited above, the mass balance model 3 (Walling and He 2001) was also used to estimate the erosion rates on the cultivated field (Fig. 1.c). It takes into account tillage contribution to erosion. For a point experiencing water erosion, variation of the total ^{137}Cs inventory A(t) (Bq m^{-2}) with time t is expressed as:

$$\frac{dA(t)}{dt} = (1-\Gamma)I(t) + R_{t,in}C_{t,in}(t) - R_{t,out}C_{t,out}(t) - R_w C_{w,out}(t) - \lambda A(t)$$
(6)

For a point experiencing deposition, the equation is:

$$\frac{dA(t)}{dt} = I(t) + R_{t,in}C_{t,in}(t) - R_{t,out}C_{t,out}(t) + R'_w C_{w,in}(t) - \lambda A(t)$$
(7)

where $C_{t,in}$, $C_{t,out}$ and $C_{w,out}$ (Bq kg^{-1}) are the ^{137}Cs concentrations of the sediment associated with tillage input, tillage output and water output respectively and R_w and R'_w are water erosion rate and water induced deposition rate respectively.

The net erosion rate R (kg m^{-2} yr^{-1}) is given by:

$$R = R_{t,out} - R_{t,in} + R_w$$
(8)

and for a net deposition site R' becomes as follows:

$$R' = R_{t,out} - R_{t,in} - R'_w$$
(9)

This model only applies to slope transects parallel to the flow directions. The effect of tillage in redistributing soil is represented by dividing a flow line down a slope into several sections and each section is approximated as a straight line, then for the ith section from the hilltop, the net soil redistribution induced by tillage R_t (kg m^{-2} yr^{-1}) is estimated by the following equation:

$$R_t = \phi\ (\sin \beta_i \ \ \sin \beta_{i-1}) / L_i = R_{t,out} - R_{t,in}$$
(10)

where b_i and b_{i-1} are the slope angle degrees before and after the sampled point, L_i (m) is the slope length of the ith segment and f (kg m^{-1} yr^{-1}) is a constant estimated from the erosion rate $R_{t,out,1} = R_1$ for an eroding point from the first segment at the hilltop (f = L_1 R_1/ $\sin b_1$). R_1 is calculated from the measured total ^{137}Cs inventory $A_1(t)$ (Bq m^{-2}) of that point, derived from the equation 4 (assuming water erosion is negligible and no tillage input to it).

Results and discussion

Quantification of the soil loss in the cultivated sites

To convert ^{137}Cs measurements into soil erosion/ deposition rates, we have selected three conversion models: the proportional model (PM), the simplified mass balance model (MBM1) and the standard mass balance model (MBM2), from the set of models developed by Walling *et al*. (2001). These models are based on the comparison of ^{137}Cs inventories in eroded or accumulated sites with the one measured in a non eroded and non accumulated site (reference inventory).

The results for both calibration models are presented in table I and Fig. 2. The annual atmospheric ^{137}Cs deposition flux I(t) (Bq m^{-2} yr^{-1}) was assumed to be equal to that estimated for United Kingdom (Cambray *et al*. 1989). The fraction of the freshly deposited ^{137}Cs eroded before being incorporated into the ploughed horizon (proportion factor g) was estimated from the local rainfall regime, its mean value is 0.3. For the relaxation mass depth H, the initial distribution of ^{137}Cs fallout in surface soils was established by multiplying the initial depth of ^{137}Cs fallout (taken from the literature, Walling and He (2001)) by the soils bulk density (B=1365 kg/m^3, H=5.5 Kg/m²).

Particle size correction was not taken into account (P=1) because no significant particle size selectivity appeared to be associated with sediment mobilisation (silt constitutes the major part of the soils). The plough depth was estimated to be 10 cm from field observations, which is coherent with the fact that cultivation practice is the animal traction. Furthermore, this plough depth is similar to the value (0.12±0.03 m) determined by (Schuller *et al*., 2003) at sites ploughed by animal traction (chisel). Finally, ^{137}Cs reference inventories were measured in three soils nor eroded or accumulated from the same watershed (Radakovitch *et al*., 2002). The three inventories are in agreement with a mean of 2582±124 Bq/m² (ó=270 Bq/m², reference date: November 1999). This mean reference inventory is similar to the value of 2655 Bq/m² in Nakhla catchment (Bouhlassa *et al*., 2000) which reflect the proximity (Fig. 1a) and the similar precipitation of the two catchments (Nakhla : 600-800mm of the mean annual rainfall). In contrast, Nouira and al., (2003) found a lower value (1630Bq/m²) in the O. El Maleh catchment, situated in the region of Casablanca (the data have been corrected to 02/11/1999). This difference in the mean value of the reference ^{137}Cs inventory may reflect the difference in precipitation between the two catchments: the mean annual rainfall in the O. El Maleh catchment is ca. 400 mm, while that in the study area of El Hachef is ca. 800 mm.

Furthermore, the value of total variability in ^{137}Cs inventories (27%) identified at the 3 reference sites of El Hachef is similar to these identified by other workers (Lance *et al*., (1986) and Loughran *et al*., (1982)).

The erosion rates obtained with the three models (Fig. 2) are in agreement when ^{137}Cs loss is low (< 20%). For higher ^{137}Cs loss, a net divergence appear between the three models. The highest erosion and deposition rates were produced by MBM1. The PM

Sample point	^{137}Cs inventory (Bq/m2)	soil erosion (-) or deposition (+) ($t\ ha^{-1}\ yr^{-1}$)		
		PM	MBM1	MBM2
1	2294	-2,0	-2,6	-2,2
2	2338	-1,5	-1,9	-1,6
3	1083	-16,3	-29,3	-25,4
4	959	-18,0	-34,3	-30,0
5	1348	-13,2	-21,6	-18,3
6	1269	-14,1	-23,7	-20,4
7	800	-18,5	-35,8	-31,3
8	749	-20,2	-42,2	-37,3
9	222	-26,4	-83,8	-78,6
10	237	-26,3	-81,6	-76,3
11	1634	-9,8	-14,7	-12,5
12	861	-19,7	-39,6	-34,7
13	2585	0,3	0,8	0,7
14	2190	-4,2	-5,7	-4,8
15	1886	-7,8	-11,2	-9,4
16	1716	-9,8	-14,6	-12,4
17	3669	12,9	28,4	24,2
18	196	-27,4	-91,5	-86,5
19	299	-26,2	-76,9	-71,2
20	3068	5,9	14,3	12,3
21	5542	34,7	83,5	71,8
22	1172	-16,1	-28,5	-24,6
23	785	-21,1	-44,4	-39,1
24	2423	-1,9	-2,4	-2,0
25	1430	-13,8	-22,2	-18,9
26	1060	-17,0	-33,3	-28,9
27	2372	-2,5	-3,2	-2,7
28	3266	8,0	18,6	15,9
29	2823	5,1	11,5	9,9
30	338	-23,9	-65,1	-59,8
31	561	-23,3	-48,5	-43,6
32	6140	43,8	100,6	86,7
33	1594	-9,2	-13,7	-11,7
34	1844	-6,3	-8,8	-7,5
35	1679	-8,3	-12,0	-10,3

Table I.- Erosion/deposition rates calculated using PM, MBM1 and MBM2[a].

erosion rates varied from 1.5 to 27.4 $t\ ha^{-1}\ yr^{-1}$ and the deposition rate varied from 0.3 to 43.8 $t\ ha^{-1}\ yr^{-1}$. The MBM1 erosion prediction varied from 1.9 to 91.5 $t\ ha^{-1}\ yr^{-1}$ and the deposition rate varied from 0.8 to 100.6 $t\ ha^{-1}\ yr^{-1}$. The MBM2 erosion varied from 1.6 to 86.5 $t\ ha^{-1}\ yr^{-1}$ and the deposition rate from 0.7 to 86.7 $t\ ha^{-1}\ yr^{-1}$. The mean erosion/deposition rates estimated with the PM were 14/16, 32/37 with MBM1 and 29/32 $t\ ha^{-1}\ yr^{-1}$ with MBM2 (Table I).

There is reasonable agreement between these values and the mean erosion rates obtained in the Nakhla basin (16, 31, 24 $t\ ha^{-1}\ yr^{-1}$**)** using respectively the three models: PM, MBM1 and MBM2 (Bouhlassa *et al.*, 2000).

In a nearby basin , Lahlou (1994) and Dahman (1994) obtained relatively high erosion rates, 28 and 32 $t\ ha^{-1}\ yr^{-1}$ using other methods. Besides, the bathymetric measurements in the Ibn Batouta dam measured 47.2 $t\ ha^{-1}\ yr^{-1}$ (Merzouki, 1992). These results obtained from other methods are similar to the results obtained by the ^{137}Cs method using mass balance models.

The PM is the simplest model. It includes only a few basic parameters, but it is likely to underestimate erosion rates, because it does not take into account the dilution of ^{137}Cs concentrations in the soil within the plough layer due to the incorporation of soil from below the original plough depth.

MBM1 represents an improvement over the proportional model by incorporating more parameters such as radioactive decay of ^{137}Cs since its deposition and the gradual 'dilution' of ^{137}Cs concentrations in the ploughed horizon, caused by the incorporation of subsoil material into the ploughed horizon by tillage.

The two models, PM and MBM1, will overestimate

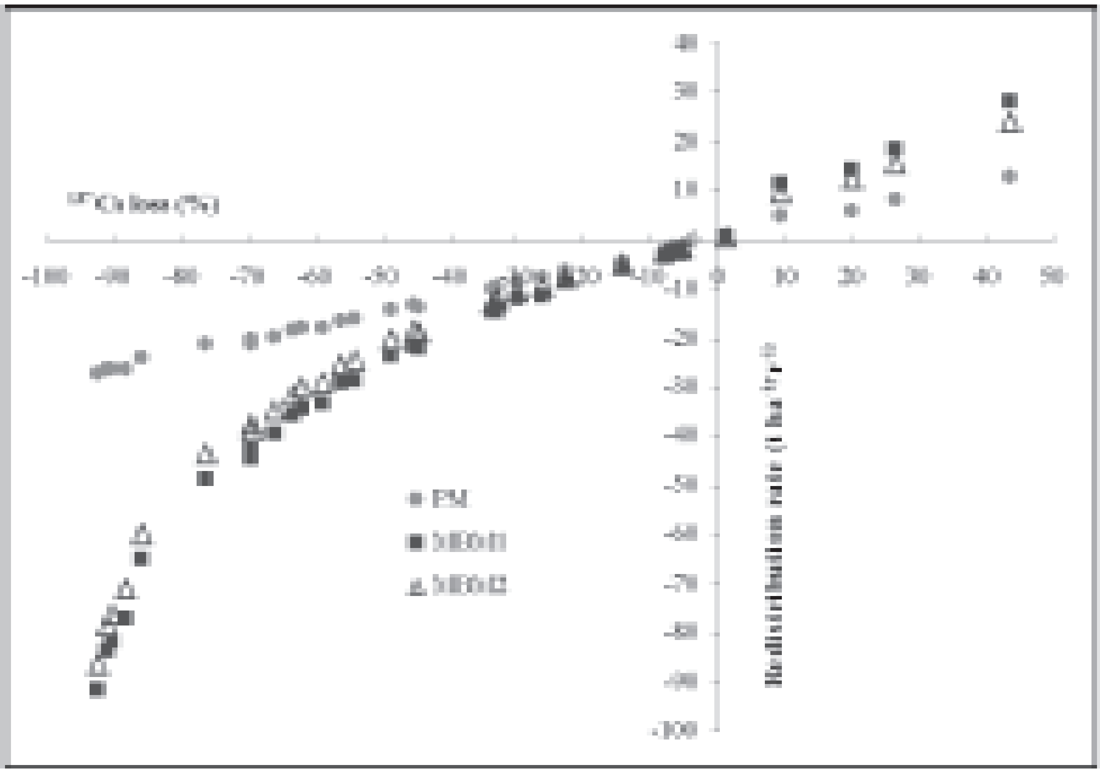

Figure 2.- Erosion/deposition rates, versus percentage of the ^{137}Cs loss/gain, using the three conversion models (PM: proportional model, MBM1: simplified mass balance model and MBM2: mass balance model2).

the rates of soil loss if some of the ^{137}Cs accumulated on the surface is removed by erosion prior to incorporation. The MBM2 attemps to overcome this limitation by taking into account both the temporal variation of the ^{137}Cs fallout and the freshly deposited ^{137}Cs fallout. Effectively, many studies confirm that the results from the MBM2 are more realistic than the PM and MBM1. Bujan *et al*. (2003) found in Pampean region of Argentin that the estimates obtained by this model correlated well with field measured soil loss.

Transects on a cultivated field

Variations of ^{137}Cs inventory along the transects

All the ^{137}Cs inventories measured along the two transects over the slope were lower than the reference inventory (Table II; no deposition points are observed). On transect H (slope length = 240m, mean slope = 12.2°), ^{137}Cs inventories varied between 939 and 2338 Bq/m^2 with a mean value of 1600 Bq/m^2. On the transect V (slope length = 240m, mean slope =

	Site	Distance (m)	^{137}Cs Inventory	Erosion rate (t ha^{-1} an^{-1}) from MBM3		
				Rt	Rw	R=Rt+Rw
Transect H	H1	0	2294	-2,6	0	-2,6
	H2	30	2338	-0,7	-1,1	-1,8
	H3	60	1083	1,1	-28,1	-27,0
	H4	120	939	-0,5	-29,6	-30,1
	H5	240	1348	0	-18,5	-18,5
Mean value			*1600*	-0,5	-15,5	-16,0
Transect V	V1	0	1268	-24,0	0	-24,0
	V2	30	900	4,1	-41,4	-37,4
	V3	60	749	2,7	-41,8	-39,1
	V4	120	222	-0,4	-82,8	-83,2
	V5	240	237	-1,8	-74,6	-76,4
Mean value			675	-3,9	-48,1	-52,0

Table II.- ^{137}Cs inventory and erosion rates R (t ha^{-1} yr^{-1}) estimated for the field transects using the mass balance model 3.

13.6°), they varied between 222 and 1269 Bq/m^2 with a mean value of 675 Bq/m^2. This lower value is an indication of higher soil loss in this transect, that can be due to the slope effect which facilitates the removal of the soils particles. The two transects show a decrease of ^{137}Cs inventory from the hilltop and a small increase at the base, suggesting a decrease of erosion downslope. The most important loss of ^{137}Cs inventory for transect V and H respectively are 91% and 64% from the reference inventory.

The different behaviour of ^{137}Cs redistribution within the two transects can be due to the different shape and slope angle which reflect a complex topography of the field, or it can be due to tillage redistribution and human effect. The mean ^{137}Cs inventory for each level from the top to the bottom of the two transects (H and V) is respectively equal to: 1782, 1619, 916, 581 and 793 Bq/m^2. But to take into account the lateral component of the displacements of the soil particles, further sampling along several transects should be carried out.

Erosion rates

The mass balance model 3 (Walling and He, 2001) was also used to estimate the erosion rates on the field transects. This conversion model permits separation and estimation of the contribution of tillage- and water-induced soil movement to the total soil redistribution.

In addition to the parameters cited above (paragraph. 3.1), the MBM3 use also the slope angle degrees and the slope length, to estimate the constant related to tillage (f). This constant was estimated from the MBM2 erosion rate for the first eroding point at the hilltop, it ranged from 38 Kg m^{-1} par year at transect H to 239 Kg m^{-1} par year at transect V.

Within the MBM3, the net erosion rate is the algebraic sum of water erosion and tillage redistribution. Table 2 resumes the contribution of the tillage redistribution (R_t) and water erosion (R_w) from each transect. These results show that the pattern of ^{137}Cs redistribution is dominated by water erosion and that the contribution of tillage redistribution remains weak. The mean tillage erosion estimated is about 0.5 t ha^{-1} yr^{-1} at transect H and 3.9 t ha^{-1} yr^{-1} at transect V (Table II). A mean net erosion is 16 t ha^{-1} yr^{-1} and 52 t ha^{-1} yr^{-1} respectively at transect H and transect V.

The pattern of the erosion rates along the two transects calculated by the all models (PM, MBM1, MBM2 and MBM3) is presented in Fig. 3. The erosion rates derived from the PM is lower than those predicted with the three other models, which are in a relatively good agreement.

Conclusions

1) The erosion rates calculated from the ^{137}Cs measurements for cultivated soils confirm the significance of soil erosion problem in El Hachef basin (north Morocco) and give evidence that the cultivated land on steep slopes is one of the important sources for land degradation, reduction of crop productivity and silting up of dams. So, the application of ^{137}Cs method provides a simple and rapid method to undertake a general diagnostic of soil erosion and hence identifies areas of prioritary intervention.

2) The mean erosion/deposition rates estimated with the PM were 14/16, 32/37 with MBM1 and 29/32 t ha^{-1} yr^{-1} with MBM2. There is reasonable agreement between these values and the mean erosion rates obtained in a nearby basin using the same models. Besides, the results obtained by the ^{137}Cs method using mass balance models, are similar to the results obtained from other experimental methods carried by other research.

On the other hand, the results from the MBM2 are considered to be more realistic than the PM since it takes into account both the temporal variation of the ^{137}Cs fallout and the freshly deposited ^{137}Cs fallout.

Nevertheless, further research on the application of the ^{137}Cs method, in particular the validation of the results obtained and the selection of appropriate model is needed.

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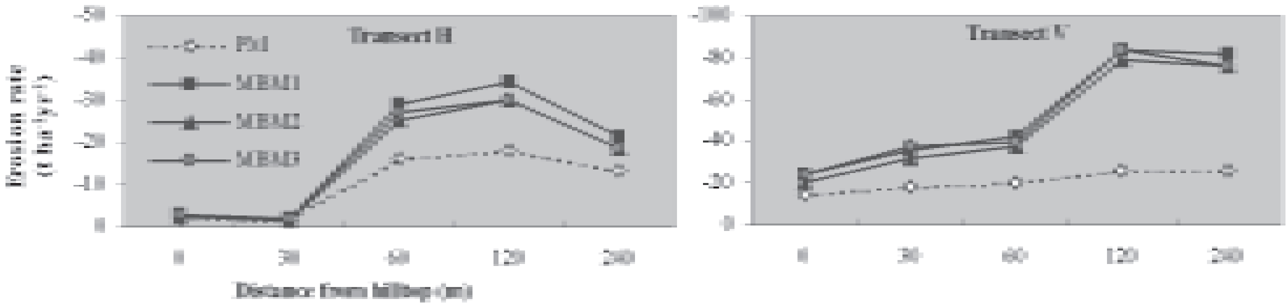

Figure 3.- Pattern of net erosion rates along the two transects calculated with Proportional model (PM), simplified mass balance model (MBM1), mass balance model2 (MBM2) and mass balance model3 (MBM3).

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