**Vertical and lateral distribution of fallout ^{137}Cs and soil properties along
representative toposequences of Central Rif, Morocco.**

Abstract

The purpose of this study is to understand and quantify the relationships between current ^{137}Cs inventories and the soil properties and the physiographic characteristics. A total of 36 cores were taken in seven transects with different slopes, lithology and land use. The analysis focused on the ^{137}Cs mass activity as well as inventories and its relationship with soil properties as grain size and organic matter.

The mass activity of ^{137}Cs and the inventories varied between 3.6 to 63.7 Bq kg⁻¹ and between 521.7 to 3304.4 Bq m⁻², respectively. At uncultivated soils, high concentrations of ^{137}Cs are located in the top 10 cm and decreased exponentially in depth. Cultivated soils record disturbed and heterogeneous ^{137}Cs profiles with values of mass activity and inventories up to 38.7 Bq kg⁻¹ and 2510.8 Bq m⁻², respectively.

The ^{137}Cs inventories were significantly higher in uncultivated soils (mean: 2086.9 Bq m⁻²) compared to cultivated soils (mean: 1397.1 Bq m⁻²). The ^{137}Cs mass activity showed a significant positive correlation with organic matter, silt and clay, but it was negatively correlated with sand and pH respectively. High levels of ^{137}Cs were found at altitudes between 500 m and 640 m a.s.l, and at slopes from 8° to 11°, as well as in dense scrub land and Fersialitic soils. A principal component analysis showed that more than 86.7% of the variance in ^{137}Cs mass activity was explained by the organic matter content and the land use.

The results of this study provide insights into the effects of soil properties and physiographic factors on the behaviour of ^{137}Cs in soils of Mediterranean environments of North Africa and strengthen the reliability of this radioisotope as an erosion tracer.

Keywords: ^{137}Cs , Soils, Physico-chemical properties, Biogeographical features, Land uses, Central Rif, Morocco

Introduction

Soil erosion is a complex process because of its unpredictable behaviour, irregular and uncertain spatial and temporal fluctuations. It is a major constraint to sustainable development and promotion of rural activities. This phenomenon affects aggressively many areas in Morocco, especially the Rif area where water and soil resources are seriously threatened (Heusch1970; Sadiki et al., 2012; Mesrar et al., 2015). At the level of the Sahla watershed, the potential risk study of erosion shows that more than 15% present high to extreme erosion level, localised especially in agricultural fields, where losses recorded as $190 \text{ t ha}^{-1} \text{ y}^{-1}$ (Mesrar, 2016).

In North Africa, especially in Morocco, several authors have used ^{137}Cs for quantifying soil loss and assessing the relationships between soil loss and physiographic factors (Benmansour et al., 2000; Bouhlassa et al., 2000; Nouria et al., 2003; Faleh et al., 2005; Sadiki et al., 2007; Benmansour, 2013). This study aims to derive information on the behaviour of ^{137}Cs taking into account the characteristics of the physico-chemical soil properties as well as the physiographic conditions existing in this region.

The use of ^{137}Cs as tracer of erosion is an old practice (McHenry, 1968). Since the 1970s, fallout ^{137}Cs ($t_{1/2} = 30.2$ years) was used to study the processes of redistribution of soil particles and their depth migration taking into account both the physico-chemical parameters

of soils and field physiography (Walling, 1983; Navas & Machin, 1991; Navas & Walling, 1992; He & Walling, 1996; Zhang et al., 1999; Zapata, 2002; Navas et al., 2005a; Mabit et al., 2008; Monna, 2009; Gaspar & Navas, 2013).

The technique assumes that the fallout of ^{137}Cs is spatially uniform and depends on the latitude and the average annual rainfall (He and Walling, 1996). The ^{137}Cs reaches the soil by the wet and dry deposition and is quickly adsorbed by clay minerals (Ritchie et al., 1970). Once adsorbed, ^{137}Cs can move down into the soil profile by the infiltration of water. The distribution of ^{137}Cs in the soil is controlled by physico-chemical properties, climatic and physiographic characteristics and land uses (Navas, 2007). The understanding of its behaviour is important for its use as a radioactive tracer and to assess its distribution in the landscape.

The physico-chemical soil properties, such as texture, structure and composition (percentage and types of clays) could have significant effects on the amount of ^{137}Cs concentrated in soils and consequently on its distribution.

The ^{137}Cs is highly correlated with the specific surface of the grain size fractions, and it has been shown that ^{137}Cs has a significant preferential adsorption by the fine soil particles (Zhang et al., 1999). According to (Rigol et al., 2002), the relationship between the sorption of the radionuclide and the mineralogical and organic components are complex and the presence in soil of a small amount of clay is sufficient for the sorption that is governed by the specific sites of the clay.

In most soils, ^{137}Cs has generally low mobility with most retention occurring in surface layers (Colle & Roussel-Debet, 2000). The organic matter in soils plays an important role in the adsorption of ^{137}Cs . This relationship has been well studied in a variety of environments (Navas et al., 2005a; Martinez et al., 2010; Gaspar & Navas, 2013). In most soil types, ^{137}Cs is selectively fixed in the clay minerals. In soils having a few percent of organic matter, the soil-solution of Cs^+ ion partition is controlled mainly by an ion exchange mechanism with the

clay minerals in particular illite (Faroussi et al., 2007). However, in organic soils, ^{137}Cs is generally more mobile; due to the high cationic exchange capacity of the organic matter.

The main objectives of this study are: i) to evaluate the behaviour of ^{137}Cs in cultivated and uncultivated soils in the central Rif (North Africa), ii) to assess the relationships between the radionuclide and some main physico-chemical properties of the soil (particle size, organic matter, electric conductivity and pH), iii) to assess the effects of biogeographical characteristics (topography, vegetation, land use, soil type and lithology) in its distribution along with selected toposequences of different land uses and soil types. This research will contribute to gain information for a more reliable use of ^{137}Cs in the Rif's landscapes and for a more consistent use of conversion models.

1 Materials and methods

1.1 Description of the study area

The Sahla catchment (Fig.1) has an elongated shape from north to south for about 35 km and 6 km wide. Its medium elevation is 562 m with the highest peak at 1129 m and 193 m at the outlet and its average slope is 17%. The Sahla River carves transversely the large anticlinal vault of Taounate wrinkle oriented east to west by a deep gorge where the Sahla dam was built. The watershed covers an area of 178.08 km². The climate is Mediterranean with dry summers and rainy winters. Rainfall is very irregular from one year to the other with an average rainfall of 600 mm. The average annual temperature is about 16 °C with temperature inversions in winter (Mesrar, 2016).

Geologically speaking, the watershed is part of the Rif's range, which occupies a key position in the system of the Alpine orogenic belt. It is the most western part of the Maghrebides chain, which stretches along the North African coast, and continues east Sicily and Calabria in southern Italy. It forms the southern flank of the Gibraltar Arc that extends south of Spain

by the Betic Cordillera (Michard et al., 2008). The watershed is very hilly and the facies are usually very brittle. Geological formations of the Taounate wrinkle consist in the study area by a Jurassic-Cretaceous series of marl overcome molassic formation composed of sandstone and conglomerates (Marçais et al., 1966). The northern part of the study area is the intra rifaine area formed by two thrust sheets; Ketama and Tangier mobile units, consisting of elements ranging from Triassic to the lower Tortonian. The Ketama unit has a flysch constituted by schist and sandstone of Cretaceous of few kilometres thick. Shale's and limestone's of the Middle and Upper Cretaceous form the unit of Tangier.

The study site (Fig.1) occupies the central part of the Sahla watershed. The lithological facies in the northern part is of black flysch match with benches of quartzitic sandstone. Going south clay and marl forms the Sahla water reservoir substrate. At the southern, marlyflysch predominate and lower alluvial terraces of fine material. The slopes are steeper and higher elevations are located at the southern part unlike the north side, where the slope length is longer and elevations are low.

1.2 Sampling

The sampling was conducted by the transect method (Mabit et al., 2007). Thirty six cores were taken along seven transects. Cores are spaced by a distance of 10 to 20 m. The chosen transects were based on factors controlling the redistribution of soil particles such as land use, soil type, lithology, slope and elevation (Fig. 2). Sampling was carried out using a manual corer. The basic cylinder, made of stainless steel with a diameter of 7 cm, was driven into the soil to a maximum depth of 30 cm, or until the bedrock is reached. The core was then extracted and sectioned into interval increments of 5 cm thick. Due to the thinness of poorly developed soils, some cores did not exceed 15 to 20 cm thick, thereby depth interval increments of 5 cm are in number of 3 or 4. The remaining 10 cores were bulk, giving a total of 122 samples (112 sectioned or interval increments and 10 were bulk cores). The positions

of the cores were determined using a GPS. Details of the distribution and physiography of the soil profiles are shown in Figure 2.

1.3 Analysis and sample processing

The samples were air dried, grinded and sieved to separate the coarse fraction (> 2 mm) of the fine fraction (<2 mm) required to calculate the inventory of ^{137}Cs and for performing analyses of soil properties, namely particle size, organic matter (OM), pH, and electric conductivity (EC), according to standard norms (CSIC, 1976).

Particle size analysis was performed by laser Coulter after destruction of the organic matter by using H_2O_2 (10%) heated at 80°C , stirring for 24 hours and sonication for a few minutes to facilitate dispersion. The organic matter content was determined by Mettler Toledo Titrator and electrode. The pH (solid-liquid ratio, 1:2.5) was measured using a pH-meter. The electrical conductivity (dS m^{-1}) (solid-liquid, 1: 5) was measured using a conductivity meter.

The mass activities of ^{137}Cs (Bq kg^{-1}) were measured using a hyper-pure coaxial germanium gamma detector with high resolution, low background noise and low power, coupled with an amplifier and a multichannel analyzer. The detector has an efficiency of 30% and a resolution of 1.9 keV (shielded to reduce background noise). It was calibrated using certified standard soil samples by CIEMAT (Spanish reference for nuclear measurements) (UTT-OTRI P5/248) in the same cylindrical geometry ($\varnothing$: 7.8 cm) as the measured samples. The gamma radiation from ^{137}Cs (661.6 keV) accounted for 30000 s, giving results with an analytical accuracy of $\pm 6\text{-}8\%$ for a confidence level of 95%. The ^{137}Cs content in the samples is expressed in concentration or mass activity (Bq kg^{-1}) and the activity per surface unit or inventory (Bq m^{-2}) is calculated using the mass of the fraction below 2 mm and the section of the corer.

2 The study transects

The transects IC (intensive crops) and CA (crops and arboriculture) occupy the highest level of the toposequence (540 m-640 m) on the north part of the study area, a Fersialitic soil developed on schist marls with a well-developed humus horizon. The slopes range from 8° to 9° and the vegetation is composed by olive and fig trees together with pear trees, in places and cannabis.

Transects DC (dense crops) and RA (rain fed agriculture) are located at the bordering part of the Sahla reservoir with average altitudes of 440.5 m and 392 m, respectively, and with slopes up to 12°. At this point, Vertisols are left fallow. Very little vegetation grows on these soils, but with irrigation and soil amendments crops can be grown. Some tree crops occupy this part of the basin (plum, pear trees and vineyards), which require large amount of water and laborious working of the soil.

The transect OC (olive trees and cereal), corresponds to Vertisols developed on marl and sandstones. Its average altitude is of 405 m and on relatively high slopes (12°); both cereals and olive trees are grown.

The transect CB (crops on terraced slopes) is located on the eastern side of the dam where the crops are grown on terraces. It occupies the lowest altitude toposequence (346 m) with an average slope of 10° and a predominant marl lithology on which poorly developed soils is dominating. The transect DM (dense matorral) is located at an average altitude of 478 m and has an average slope of 8.8 °. The vegetation cover is green oak that shows some disturbance due to livestock grazing what might have an influence on the distribution of ¹³⁷Cs. Soils are formed from colluviums material that moves downwards by gravity and runoff on slopes formed on marls and sandstone colluviums. Soils are Vertisols with clearly differentiated soil horizons. The transect OM (open matorral) occupies the highest altitudes (550 m) at the south of the catchment side. Soils are shallow and little evolved and developed on marls intercalated

with quartzite sandstone. The vegetation cover is a scrubland more or less degraded composed mainly by green oak and dwarf palm (local name: Doum).

At selected sites, most soils do not reach a high degree of development because the steepness of the slopes and associated lengths subject them to continuous erosion. As a consequence, the contents of finer fractions and organic matter quickly decrease. Among these soils, Vertisols are the best developed soils formed on marls at protected areas or on gentle slopes. On stiff materials (sandstone, quartzite and quartzite sandstone), when conditions are favourable Fersialitic soils are developed.

3 Statistical analysis

Statistical analyses include measurement of central tendency, measures of variability, and a measure of shape was used to define linearity of data. Of particular interest, the standardized skewness and kurtosis has been used. Values of these statistics outside the range (-2, +2) indicate significant departures from normality, which would tend to invalidate many of the statistical procedures normally applied to this data, like Pearson correlation coefficient. In this case, to normalize the variables, the LOG(Y) transformation has been used.

Statistical analysis was conducted using the method (LSD) Fisher and Kruskal-Wallis to determine whether there are significant differences in the variables analysed or in other words determining the values null hypothesis that the test rejects with $P < 0.05$ at 95% confidence interval.

The examination of the relationships between ^{137}Cs and the physico-chemical properties of soil and physiographic features is done through correlations. The Pearson correlation coefficient is used to measure the strength of the linear relationships between physico-chemical properties with activities and inventories of the radioisotope. The analysis of variance (ANOVA) was used to investigate the significant differences of the average variance between the mass activity, inventories and physiographic factors (land use, soil types,

vegetation and lithology, slope, altitude). Finally, principal components analysis (PCA) was conducted to reduce the number of variables and factors. Indeed, PCA reduced dimensions revealing several underlying components, known as the main components. They are defined as a linear combination of the original variables.

4 Results and Discussion

4.1 Physiographic and physico-chemical characteristics of the study soils

Soils at the study sites are alkaline in cultivated soil (n=93) with a pH ranging from 7.34 to 8.71. However, in uncultivated soil (n=29) the pH is ranging between 5.07 and 7.43 (Table 1), we note that the variability of the pH is very low with standard deviation less than 0.44. All soil samples (n=122) show an abundance of the fine fraction (<2 mm) with an average of 84.5% in which the average proportion of the clay fraction reaches 28.3%. Silt is the predominant fraction with an average rate of 63.8% whereas the sand is the least abundant fraction (7.9%). The average organic matter content is 1.6% ranging from as little as 0.3% up to 11.5% with the highest percentages recorded at surface horizons of dense matorral.

The cultivated and uncultivated soils showed significant differences ($P < 0.05$) with regards to contents of organic matter, fine fraction (<2 mm) and values of pH and electric conductivity, and as lightly difference of clay and silt that does not exceed 5%. The uncultivated soils exhibited higher levels of organic matter and highest percentages of clay, which is characteristic of Fersialitic soils, often used for cereal crops.

At deeper levels, variations in physical and chemical properties differ between cultivated and uncultivated soils (Fig.3). The clay, silt and sand contents are usually distributed evenly for all land uses.

For uncultivated soils the pH is lower and significantly different ($P < 0.05$) than in cultivated soils and also decreases slightly with depth as the EC does (Fig.3). For uncultivated soils, organic matter content recorded an exponential decrease with depth and showed large variability. In cultivated soils, the depth distribution of organic matter is much more homogeneous showing slightly lower values at deeper layers. The pH becomes more basic and conductivity, which is slightly higher than in uncultivated soils, tends to decrease with depth. The variation of the soil properties both in the soil profiles and at the sampling sites of the different transect reflects the heterogeneity of soil types, land uses and vegetation cover.

4.2 Distribution of ^{137}Cs along the transects

The mass activities and inventories of ^{137}Cs in the 36 cores vary largely as indicated in Table 2. The values of mass activity range between 3.6 and 63.7 Bq kg⁻¹ with an average of 18.1 Bq kg⁻¹ and a coefficient of variation of 68%. The highest values recorded in uncultivated soils average 31.2 Bq kg⁻¹. The values of inventories range from 521.7 to 3304.4 Bq m⁻². The mean values for all cores is 1509 Bq m⁻² varying between 1319 Bq m⁻² measured in cultivated soils and 2087 Bq m⁻² for uncultivated soils with a coefficient of variation of 43.4%. This large variation in the ^{137}Cs contents along the transects is mainly linked to soil processes such as erosion and the type of land use besides the physico-chemical characteristics, including the percentage of organic matter and size fractions influence the values of the radioisotope. The distribution in depth of ^{137}Cs in uncultivated soils (Fig. 4) shows exponential deviation with depth and high percentage at the surface, However, in cultivated soils the variation can be related to soil tillage.

Figures from 5 to 8 show the ^{137}Cs depth distribution along transects and in each soil sample IC-CA (Fig. 5), RA-DC (Fig. 6), CB-OC (Fig. 7) and DM-OM (Fig. 8), as well as their physiographic characteristics, soil type, lithology, vegetation cover type, height and length. In the sectioned profiles the distribution of mass activities and inventories of ^{137}Cs are

significantly different with depth. Most of ^{137}Cs was concentrated in the top 20 cm. In the uncultivated transects, the ^{137}Cs profiles have the typical depth distribution of the radionuclide found in undisturbed soils, thus, there is a high concentration in the top 10 cm and an exponential decrease with depth. In the cultivated soils, the ^{137}Cs is mixed thoroughly within the plough layer (0-15 cm). The cultivated profiles present high variability of the mass activities and inventories of ^{137}Cs .

Table 3 shows that the transect IC presented mass activities ranging from 6.5 to 30.4 Bq kg⁻¹ and inventories of 521.7 to 1918.1 Bq m⁻². The transect CA which is the prolongation of the transect IC down slope showed mass activities values of 12.4 to 24.4 Bq kg⁻¹ corresponding to inventories of 895.2 to 2359.5 Bq m⁻², respectively. In the lower elevations transects RA, DC, CB and OC presented mass activity values of 5.2 to 38.7 Bq kg⁻¹ and inventories between 771.3 and 2510.8 Bq m⁻². The transects DM and OM on uncultivated soils showed mass activity values ranging from 13.4 to 27.3 Bq kg⁻¹ corresponding to inventories of 646.1 to 2535.5 Bq m⁻² for OM and values ranging from 21.0 to 63.7 Bq kg⁻¹ corresponding to inventories of 1370.0 to 3304.4 Bq m⁻² for DM.

The lowest ^{137}Cs mass activities were recorded in intensive crops (IC) on blue marls substrate, the highest were on dense matorral (DM) on poorly developed soil. The ^{137}Cs inventories were also quite high in uncultivated areas with averages between 1590.8 and 2285.4 Bq m⁻² whereas for the cultivated area the values were ranged from 1196.8 to 1439.7 Bq m⁻².

These results are similar to other studies in Morocco, with regards to climate variability and topographic characteristics. At the Nakhla catchment (South of Tetouan) on seven uncultivated sites, inventories ranged from 1671 to 3850 Bq m⁻², for an average rainfall of 732 mm (Bouhlassa et al., 2000). On cultivated soils in the same catchment, mass activity values do not exceed 6.5 Bq kg⁻¹ and inventories are estimated between 426 and 777 Bq m⁻² (Damnati al., 2010). In uncultivated soils of the Oued El Maleh catchment (Ain Harouda

Region), the inventory values are 383-1385 Bq m⁻² (Nouira et al., 2003) for an annual rainfall that does not exceed 400 mm. In the Aknoul catchment (Eastern Rif), the inventory values range between 881 and 5788 Bq m⁻² for a 471 mm of rainfall (Faleh et al., 2005). South of Tangier (El Hachef catchment) the inventories are 196 - 2294 Bq m⁻² for precipitations around 800 mm (Ibrahimi et al., 2005).

¹³⁷Cs depth distribution differs markedly between uncultivated and cultivated soils. The firsts are the best preserved (DM and OM) because the soil maintains the original non-disturbed conditions as evidenced by the ¹³⁷Cs contents that decrease exponentially with depth. The maximum activity recorded is found at the soil surface. The cultivated soils are the most disturbed, showing both soil mixed by tillage within the plough layer and below a change again to the decreasing distribution of ¹³⁷Cs in depth as seen in profiles of transects IC, CA, OC and DC.

Along the transects, slope and its length influenced the downward movement of ¹³⁷Cs as indicated by the ¹³⁷Cs inventories that in most cases are higher compared to the values in the next upslope core. The decrease of ¹³⁷Cs in the upper layers (5 to 15 cm) indicates that the losses mainly affect the soil surface and it does not progress into the deep layers.

The seven study transects have similar climatic conditions, therefore, the large fluctuation of the vertical and lateral distribution of ¹³⁷Cs can be explained partly by the variability of soil properties such as the grain size distribution and the proportion of organic matter, as well as other physiographic factors, such as land use, vegetation cover and topography (slope and altitude). Physical soil processes induced by runoff seems to play a key role in the final distribution of ¹³⁷Cs. Land use exert an important influence on the soil protection thus the soils were much better preserved under the matorral, in agreement with results found in similar environments (Quine et al., 1994; Sadiki et al., 2007).

4.3 Relationships of ^{137}Cs with soil properties and physiographic factors.

The mass activities of ^{137}Cs in the bulk cores have shown significant positive correlations with silt and to a lesser extent with soil fine fraction (<2 mm), organic matter and clay. The lowest positive correlation was with the electrical conductivity. ^{137}Cs is negatively correlated with sand, the coarse fraction (>2 mm) and pH (Table 4). Although the correlations are stronger for mass activities of ^{137}Cs than in inventories, the same type of correlations (positive or negative) applied for the ^{137}Cs inventories.

In cultivated soils, silt is the only soil property that was significantly positively correlated with the mass activities and inventories of ^{137}Cs . However, these values were inversely correlated with sand and pH.

In uncultivated soils, the ^{137}Cs mass activities were positively correlated with clay, silt and organic matter. It therefore reflects the adsorption of ^{137}Cs through their high cationic exchange capacity (Navas et al., 2005b, Gaspar & Navas, 2013). Indeed, lithological characteristics of the underlying substrate that may be favourable to explain the significant negative correlation between the ^{137}Cs with pH and EC.

ANOVA of the mass activities and inventories of ^{137}Cs in function of the physiographic factors showed differences in their means for some of the studied factors as shown in figure 9. Higher mean values of ^{137}Cs were registered in uncultivated soils, where matorral are dense. Elevations which show a maximum of fallout ^{137}Cs are located between 500 m and 640 m and for slopes between 8° to 11°. The means of ^{137}Cs values are higher in Vertisols and Fersialitic soils compared with poorly developed soils. The soils on quartzite-sandstone facies had lower values of ^{137}Cs in comparison with limestone-sandstone colluviums. On cultivated soils, slopes recording a high amount of ^{137}Cs in terms of inventory belong to the class 5°-8°, while the one with a high mass activity belongs to the slope class 8°-11°, facies of blue marls and marls and sandstone had lower amount of ^{137}Cs compared to the marlyflysch.

319 These results show the key role of land use, cover type and bioclimatic conditions in the
320 distribution of the radioisotope in soils. The majority of soils in the Sahla catchment are
321 cultivated, while the surface occupied by dense and open matorral that provide important
322 protection to the ground does not exceed (10%). The combination of little extension of the
323 protective vegetation cover together with the intensive land use determines the complexity of
324 the distribution ^{137}Cs distribution in the landscape.

325 The results of a principal component analysis showed that the combination of parameters
326 explained a relatively high proportion of 86.7% of the total variation between samples. Four
327 components with an Eigen value greater than 1 were retained (Table 5 and Fig.10). Higher
328 values were assigned to the variables associated with the fine fraction (≤ 2 mm), the organic
329 matter and clay contents. It reflects the high mass activity of ^{137}Cs in the uncultivated soils,
330 Vertisols particularly on steep slopes, dense scrubland and high percentage of organic matter.
331 In cultivated soils the mass activities of ^{137}Cs were low on gentle slopes where soil organic
332 matter and the fine fraction ($< 2\text{mm}$) were also low, however, the percentage of clay was
333 relatively high.

334 The second component explained 23.2% of the total variance and is associated to the
335 percentages of silt and clay in the presence of organic matter, with negative correlation with
336 the sand fraction. The third component explained 12.5% of the variance and reflected the
337 elevation control in association with contents of silt and organic matter. The fourth
338 component, that explained 11% of the total variance, showed high values of slope and the
339 clay fraction as associated to high ^{137}Cs mass activities.

340 The degree of linear dependence between variables in the case of inventories explains 75.5%
341 of the total data variability. The first component explains 30.4% of the variance with high
342 dependency is organic matter (the > 2 mm fraction). In consideration of clay, silt, sand and
343 the < 2 mm fraction show a negative dependence. The second component explains 21.1% of

variance is characterized by high positive contribution of clays, silts and particularly organic matter. The third component accounts for 13.1% of the variance and shows a negative contribution of almost all parameters, except for the <2 mm fraction and elevations. The fourth component explains 10.9% of variance and reveals a strong contribution of organic matter and the > 2 mm fraction. The altitudes are inversely related, so that the slope is positively correlated to ^{137}Cs . The results of PCA analysis including the ^{137}Cs inventories were quite similar to that of ^{137}Cs mass activities, but comparing the first component of activities with the corresponding inventory, we note that the parameters that correlate negatively with inventories correlate positively with activities. These results come to the work of Gaspar (2011) in an environment close to the Sahla watershed.

In both PCA cases, the parameter weights were distributed on four components. Although mathematically speaking, the principal component analysis cannot be used to make predictions it was able to detect the strength of the relationships between parameters analysed with ^{137}Cs in all cores and the results are consistent with the conclusions drawn from the correlation analysis.

5. Conclusions

This study describes the pattern distribution of ^{137}Cs in heterogeneous environments such as the complex mosaic of land use and soil types found in the hilly landscapes of the Rif Mountains. Cultivated and uncultivated soils show significant differences in the depth distribution of both ^{137}Cs and soil properties. The knowledge of the distribution of ^{137}Cs in soils is important to understand the behaviour of this radionuclide and, therefore, to interpret the information it provides as soil tracer.

The variation of ^{137}Cs is closely related to that of organic matter as they have a similar pattern distribution in the soil profiles. The contents of silt and clay come second in the relationships with the radionuclide. This can be explained by the absorption properties that have these components considered as soil colloids with high cationic exchange capacity and ^{137}Cs which is highly reactive will behave as a cation in a similar way as Ca^{2+} or Mg^{2+} .

Some physiographic factors strongly influence the vertical and lateral distribution of ^{137}Cs in the soils of the Sahla catchment. Among the physiographic factors, the land use exerts the strongest influence on the distribution of ^{137}Cs . Second come the elevation and slope gradient. The organic matter content is related to the land use, which largely explains the similarity of correlations between the radioisotope and these two factors.

Understanding the factors and processes that significantly influence the ^{137}Cs distribution represents a promising basis for the development and the calibration of predictive models using this radioisotope as a tracer of the redistribution of soil particles.

This study aims to give reliability to the use of fallout ^{137}Cs as tracer of soil erosion and reduce the experimental and economic costs associated with its application. The results could provide a basis for interpreting the distribution of ^{137}Cs in the landscapes of the study area or in other neighbouring Mediterranean environments with similar physiographic and bioclimatic conditions.

Acknowledgments

Gamma spectrometry analyses and soil physical and chemical analyses were performed in the laboratory of Group of “Erosion and Evaluation of Soils and Water” of the Experimental Station of Aula Dei, CSIC, Zaragoza (Spain). Thanks, are given to the project AECID (AP / 037 737/11, 2011) that facilitated the initial research and to project CGL2014-52986-R.

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Fig.1. The Sahla catchment and the location of the study transects.

IC : Intensive Crops; CA : Crops and Arboriculture; CB : Crops on terraced slopes,
 OC : Olive trees and Cereal; RA : Rainfed Agriculture; DC : Dense Crops,
 DM : Dense Matorral and OM-Open Matorral

Fig.2. Distribution of cores and samples along the transects.

Fig.3. Variations in depth of physico-chemical properties

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Fig.3. Distribution in depth of ^{137}Cs in uncultivated and cultivated soils

Legend :

Fig.4. Vertical and lateral distribution of ^{137}Cs in transects IC and CA

Legend :

Fig.5. Vertical and lateral distribution of ^{137}Cs in transects RA and DC

Legend :

Fig.6. Vertical and lateral distribution of ^{137}Cs in transects CB and OC

Legend :

Fig.7. Vertical and lateral distribution of ^{137}Cs in transects DM and OM

Fig.8. Box plots of the distribution of ^{137}Cs mass activities and inventories according to the different physiographic factors in cultivated and uncultivated soils. Different letters at the top of the box indicate significant differences at the p-level < 0.05 between different classes for each factor. “The central box covers the middle half of the data (extending from the lower quartile to the upper quartile); the whiskers show the location of the smallest and largest data values; the circles indicate outlier; the line within the box indicates the median of the data (50th percentile); and the plus sign (+) indicate the sample mean”.

Fig.9. Chart grouping variables in the principal component analysis and Eigenvalue (A: mass activities (Bq.kg⁻¹); B: inventories (Bq.m⁻²))

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Table 1. Summary statistics of the soil properties.

	n	Clay %	Silt %	Sand %	<2mm %	>2mm %	OM %	pH	ECdSm⁻¹
Total	122								
Mean		28.3	63.8	7.9	84.5	15.5	1.6	7.80	0.12
SD		10.8	11.8	15.4	15.2	15.2	1.7	0.78	0.05
CV %		38.1	18.6	194.8	18.0	98.1	108.1	10.1	43.3
Min		6.5	16.0	0.0	25.6	0.09	0.3	5.07	0.02
Max		54.9	79.8	74.9	99.9	74.7	11.5	8.71	0.29
Cultivated	83								
Mean		28.9	63.8	7.30	90.3	9.8	1.0	8.26	0.14
SD		12.1	12.5	15.1	11.7	11.7	0.4	0.17	0.03
CV %		41.8	19.6	206.9	12.9	119.6	39.5	2.10	25.1
Min		6.5	21.5	0.0	31.3	0.1	0.3	7.79	0.09
Max		54.9	79.8	70.0	99.9	68.7	1.9	8.71	0.28
Cultivated bulk cores	10								
Mean		17.3	50.7	31.9	68.1	31.9	1.8	7.79	0.16
SD		5.9	12.9	17.1	10.5	10.6	1.2	0.31	0.05
CV %		34.3	25.5	53.7	15.5	32.9	65.5	4.06	33.4
Min		9.1	16.0	13.8	51.9	8.0	0.6	7.34	0.08
Max		27.8	60.3	74.9	91.9	48.1	4.3	8.59	0.24
Uncultivated	29								
Mean		30.5	68.2	1.30	73.7	26.4	3.1	6.50	0.06
SD		3.9	3.6	2.5	15.9	15.8	2.9	0.44	0.05
CV %		13.1	5.2	196.1	21.4	59.9	95.7	6.81	78.5
Min		24.1	60.3	0.0	25.3	7.7	0.6	5.07	0.02
Max		39.7	73.2	11.9	92.3	74.7	11.5	7.43	0.28

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Table 2: Summary statistics of ¹³⁷Cs mass activities and inventories

	¹³⁷Cs Bq kg⁻¹			¹³⁷Cs Bq m⁻²		
	Cultivated	Cultivated bulk cores	Uncultivated	Cultivated	Cultivated bulk cores	Uncultivated
n	19	10	7	19	10	7
Mean	19.3	6.5	31.2	1397.1	1318.6	2086.9
SD	7.5	2.1	16.4	474.6	498.2	906.6
CV %	39.1	31.7	52.7	33.9	37.8	43.4
Min	6.5	3.6	13.4	521.7	895.3	646.1
Max	38.7	10.6	63.7	2510.8	2359.5	3304.4

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Table 3: Summary statistics of ^{137}Cs activities and inventories on transects.

<i>Transects</i>	C					NC		
	IC	CA	OC	RA	CB	DC	DM	OM
	$^{137}\text{Cs Bq kg}^{-1}$							
n	7	10	3	3	4	2	5	2
Mean	17.4	19.3	20.7	14.1	6.9	31.6	35.5	20.3
Median	17.6	20.1	20.6	13.5	6.9	31.6	30.0	20.3
SD	7.4	5.5	1.0	6.6	1.7	10.1	17.3	9.8
CV %	42.7	28.6	4.7	46.7	24.6	31.9	48.7	48.3
Min	6.5	12.4	19.8	7.9	5.2	24.4	21.0	13.4
Max	30.4	24.4	21.7	21.0	8.9	38.7	63.7	27.3
	$^{137}\text{Cs Bq m}^{-2}$							
Mean	1196.8	1399.9	1439.7	1373.9	1358.2	2062.5	2287	1590.8
Median	1074.4	1328.3	1469.9	1496.7	1242.4	2062.5	2226	1590.8
SD	533.7	225.9	62.3	551.5	489.4	634.0	783.7	1336.0
CV %	44.6	16.1	4.3	40.1	36.0	30.7	34.3	84.0
Min	521.7	895.2	1368.0	771.3	903.6	1614.1	1370.0	646.1
Max	1918.1	2359.5	1481.1	1853.7	2044.6	2510.8	3304.4	2535.5

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Table 4. Pearson correlation between ^{137}Cs and the soil properties

	$^{137}\text{Cs Bq kg}^{-1}$				$^{137}\text{Cs Bq m}^{-2}$			
	Total	Cultivated	Cultivated bulk	Uncultivated	Total	Cultivated	Cultivated bulk	Uncultivated
n	36	19	10	7	36	19	10	7
^{137}Cs	0.76	0.89	0.46	0.79	0.76	0.89	0.46	0.79
Clay%	0.17	-0.27	0.39	0.34	0.07	-0.31	0.52	0.44
Silt %	0.35	0.28	0.11	0.23	0.01	0.08	0.37	0.21
Sand %	-0.34	-0.21	-0.22	-0.14	-0.05	-0.05	0.68	-0.48
<2mm%	0.28	0.17	0.44	0.32	0.11	0.40	0.55	0.34
>2mm%	-0.28	-0.17	-0.44	-0.02	-0.11	-0.40	-0.55	-0.04
OM %	0.18	0.31	0.14	0.31	0.32	0.31	0.01	0.20
pH	-0.34	-0.41	-0.35	-0.07	-0.39	-0.31	-0.67	-0.40
EC dS m⁻¹	0.13	0.09	-0.21	0.93	0.03	0.04	-0.14	0.64

545 Bold face numbers are significant at $p \leq 0.05$.

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Table 5. The first four components of the PCA analysis

	^{137}Cs (Bq kg^{-1})				^{137}Cs (Bq m^{-2})			
	PC1	PC2	PC3	PC4	PC1	PC2	PC3	PC4
^{137}Cs	-0.25	0.32	0.01	0.13	0.40	0.05	-0.23	-0.01
Clay %	0.24	0.41	-0.27	0.10	-0.28	0.38	-0.29	0.15
Silt %	0.10	0.44	0.47	-0.03	-0.21	0.43	0.44	-0.01
Sand %	-0.21	-0.54	-0.19	-0.03	-0.30	-0.52	-0.16	-0.07
OM %	0.35	0.26	0.21	-0.68	0.28	0.36	-0.13	0.65
ECdS m^{-1}	0.17	-0.07	-0.01	-0.05	-0.15	-0.14	-0.04	-0.02
pH	-0.39	-0.34	-0.07	0.08	-0.30	-0.42	-0.08	0.09
<2mm %	0.51	0.07	-0.10	-0.17	-0.47	-0.07	-0.21	-0.22
>2mm %	-0.51	-0.07	0.10	0.17	0.47	0.07	0.21	0.22
Elevation	0.03	-0.20	0.70	-0.29	-0.03	-0.22	0.66	-0.32
Slope $^{\circ}$	-0.04	0.06	-0.34	0.60	0.04	0.10	-0.31	0.59

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