**Relating intensity of soil redistribution to land use changes in
abandoned Pyrenean fields using fallout caesium-137**

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ABSTRACT

Fallout caesium-137 has been used to trace soil redistribution in abandoned fields located in the Central Spanish Pyrenees. A total of 28 fields with different lengths, slope angles and time since abandonment were selected on a representative south facing slope of the Estarrún valley. The local reference inventory and the magnitude and spatial distribution of ^{137}Cs inventories within these fields were documented and used as a basis for assessing patterns of soil redistribution. The local reference inventory was estimated to be 4500 Bqm^{-2} . Within the fields, the average ^{137}Cs inventory at the top of the slope was 3920 Bqm^{-2} and accumulation of soil at the bottom of the slopes was demonstrated by an average ^{137}Cs inventory of 5320 Bqm^{-2} . Deviations from the reference inventory were highest for fields with the longest slopes that had been abandoned for less than 30 years. Here, increases in the ^{137}Cs inventory, relative to the reference inventory, in excess of 20% were found at the bottom of the slopes. Considering all the fields and all geomorphic positions within the fields, the greatest ^{137}Cs losses and gains were found in the fields with the longest duration of abandonment, indicating more intense soil redistribution. Irrespective of the timing of abandonment, the ranges of ^{137}Cs inventories in the fields were found to be proportional to the water erosion index. The ^{137}Cs technique demonstrated that patterns of sediment redistribution were closely related to the topographic and physiographic characteristics of the slopes.

KEY WORDS: Soil movement, ^{137}Cs , profile distribution, WEI index, Central Spanish Pyrenees.

INTRODUCTION

Land degradation is usually related to the impact of agriculture on the soil system as a consequence of the soil erosion, loss of carbon, compaction and deforestation (Nagaraja et al., 2016; Bruun et al., 2015; Colazo & Buschiazzi, 2015; Taguas et al., 2015). However, the farmland abandonment can also trigger desertification processes in some environments (Mohawesh et al., 2015; Adugna & Abegaz, 2016; Hombegowda et al., 2016) especially if poor soil conditions at the time of abandonment and limitations for natural recovery of the vegetation prevail.

Farmland abandonment during recent decades has raised environmental concerns related to increased soil loss and changes in its hydrological response. The relationships between land use change and the intensity of erosion has been advised in IPCC reports. Lack of detailed understanding of relationship between land use change and erosion hampers earth system simulation of projected changes over the coming century as population increases and then plateaus and agricultural practice focuses on intensification.

In the central mountains of the Spanish Pyrenees, anthropogenic pressure on the soil resource through farming and grazing has existed for several centuries. As a consequence of intensive land use, the natural forest was progressively cleared (Alonso-Sarría et al., 2016; Quijano et al., 2016). However, in the last few decades major socioeconomic changes have caused migration of the rural population of the area to the large main cities of Northern Spain. According to Lasanta (1989), the proportion of the farmland that was abandoned in the Spanish Pyrenees reached as much as 74%, with the greatest proportion of abandoned land being found in the central mountains of the

Pyrenees. A sharp peak of land abandonment occurred in the middle years of the 20th century, from the mid 1950s to the mid 1960s, a period of increased migration from rural to urban areas caused by rapid industrial development in adjacent urban areas (Navas et al., 1997). There is evidence that this period was marked by high sediment loads in the rivers and increased sedimentation in reservoirs, although it also coincided with a period of increased flood magnitude (Valero-Garcés et al., 1999; Navas et al., 2009). Since then, several periods of accelerated land abandonment have occurred and the process still continues, due to European agricultural policies that encourage abandonment of marginal and non-productive land also producing the reduction of overgrazing (Papanastasis et al., 2015).

Several authors have described the impact of abandonment on the geomorphological and hydrological processes operating on the slopes and particularly its effects on infiltration, runoff and erosion, which have been widely documented (Ruiz-Flaño, et al., 1991; Lasanta et al., 1995, Navas et al., 1997; García-Ruiz & Lana-Renault, 2011; Nadal-Romero et al., 2016). Severe soil losses have been described in some areas, resulting in the complete removal of the upper soil horizons by erosion and it is very common to find stone pavements and pedestal plants. García-Ruiz et al. (1995) found a strong correlation between the land use (cultivated with cereals or pasture) in a field at the time of land abandonment and subsequent soil loss, with highest soil losses occurring from fields abandoned after harvest thus leaving the soil surface bare and exposed to erosion processes. Although at present most abandoned lands are naturally revegetated with shrubs and small trees, patches of bare soil surfaces appear on steep non vegetated parts. The difficulties experienced by plants in colonising abandoned land have been reported by several authors (e.g. Brown, 1991). Research in other mountain areas has investigated the controls on the success of plant recolonization after land

abandonment and has highlighted the influence of key factors such as slope steepness and aspect (Navas et al., 2008).

The use of Caesium-137 (^{137}Cs) to quantify soil redistribution is a technique that has been increasingly widely applied during the last three decades (e.g. Ritchie et al., 1970; Walling et al., 1986; Navas & Walling, 1992; Quine et al., 2003, IAEA, 2014). Fallout ^{137}Cs has been successfully used to quantify mean annual soil erosion rates over the past ca.50 years in very diverse environments (De Jong et al., 1986; Walling & Quine, 1992; Quine et al., 1999; Zhang et al., 2003; Navas et al., 2007, Navas et al., 2013). However, there have been few attempts to exploit its potential to document the rates and patterns of soil redistribution that have occurred as a result of land use change in Mediterranean environments over relatively short periods of time.

Previous research in different locations in Mediterranean environments (Navas & Walling, 1992; Sadiki et al., 2007; Mabit et al., 2012; Benmansour et al., 2013; Gaspar et al., 2013; Navas et al., 2014) has shown a high spatial variability in the distribution of ^{137}Cs across the landscape and has highlighted the need to focus on specific geomorphic units or landscape sections where the processes operating on the soil are more homogeneous (Navas et al., 2005). This high spatial variability also has implications for the cost of applying the radiometric technique, because in order to obtain representative results it is necessary to analyse large numbers of soil samples. There is a need to assess the reproducibility of ^{137}Cs data by comparing results from multiple point samples with those provided by composite samples collected at the same geomorphic position.

In this paper, we examine the potential for using ^{137}Cs as a tracer of soil redistribution associated with land abandonment in mountain areas. To address this aim, a total of 28 fields, surrounded by stonewalls and characterized by different lengths,

slope steepness and timing of abandonment, were selected on a representative south-facing slope in a mountain valley within the Central Spanish Pyrenees. The changes in land use and surface condition that occurred in these fields as a result of abandonment and the variable timing of the changes precluded the use of existing conversion models to provide precise estimates of soil redistribution within each field (e.g. Walling and He, 1999). However, by comparing the proportion of ^{137}Cs gained or lost at individual sampling points, in relation to the local reference inventory for the study area, it is possible to provide an indication of the intensity of soil redistribution by erosion and its relationship with the process of land abandonment or with topographic factors. Furthermore, differences in the intensity of soil redistribution could be expected in function of the timing of abandonment. The approach adopted in this study was aimed at documenting soil redistribution along downslope transects in individual fields and examining the role of factors such as topography, soil texture, land use and the timing of land abandonment in causing differences between fields. Considering the time span of ^{137}Cs fallout from 1954 to 1983 with a maximum peak in 1963, fields abandoned before its fallout should have undisturbed ^{137}Cs profiles denoting not mixing by tillage. In contrast, cultivated fields abandoned after ^{137}Cs fallout or still in use will show mixed ^{137}Cs profiles by tillage.

MATERIAL AND METHODS

Study site and soil sampling scheme

The south facing slopes of the Pico Sayerri mountain (2036 m a.s.l.) in the Estarrún valley were selected as the study site. The site is underlain by Eocene clays and marls. The areas most affected by anthropogenic pressure are located between 700 to

1400 m a.s.l. and coincide with areas of moderate to intense erosion. The climate is sub Mediterranean with Atlantic influence. Mean annual rainfall is around 800 –1000 mm in the valley bottom and it reaches 2000 mm at the catchment divides. The soils are primarily Calcaric Regosols, with high carbonate contents (~35%), alkaline pH and low organic matter contents (average between 2.5 and 3%). On the south facing slopes, the natural vegetation is known as “quejigal”, and is composed of *Quercus gr. faginea* and submediterranean shrubs. The north facing slopes support pine forests (*Pinus sylvestris*).

The 28 fields included in the study were located at altitudes between 1200 and 1300 m and were carefully selected to create a set of fields representative of the most common physiographic conditions in the region and different times of abandonment. The fields had been previously used for cereal cultivation (barley and wheat) and at present they are covered by Mediterranean shrub species (wild rose, genista, white hawthorn) and grasses. The basis for the field selection was a previous survey designed to document the land use history of the individual fields and the timing of abandonment and to analyse the processes of vegetation recovery after land abandonment (Molinillo et al., 1997).

The individual fields are completely surrounded by stonewalls and, in consequence, minimal import or export of sediment to or from the fields is expected to occur. Of the 28 fields (Fig. 1), a total of 14 fields had been abandoned for more than 30 years at the time of sampling in 1996, and for these fields the periods elapsed since abandonment ranged from 30 to more than 60 years. The remaining 14 fields included 6 fields still in use as meadows for grazing, but not currently tilled and 8 fields that were abandoned less than 30 years before sampling. A summary of the characteristics of the fields investigated is presented in Table 1.

The length of the fields along the slope and slope angles were measured by field survey. The lengths ranged from 24 to 124 m and the slope angles from 8 to 30 degrees. The individual fields were also characterized by their water erosion index (WEI). The WEI index attempts to reflect the susceptibility of a field to water erosion, based on well-established relationships between overland flow intensity and slope length and gradient (e.g. Zingg, 1940; Musgrave, 1947; Smith and Wischmeier, 1957; McCool *et al.*, 1987; Govers, 1991). The WEI index is estimated using the equation:

$$WEI = S^m L^n \quad (1)$$

Where:

S = gradient (m/m)

L = length (m)

Typically, values of the slope length exponent 'n' vary between 0 and 1 and most studies indicate an exponential increase of overland flow erosion with slope angle, i.e. $m > 1$. Govers (1991) found that the relative slope effect when 'm' equals 1.45 is almost identical to the USLE slope factor as proposed by Wischmeier and Smith (1978) and revised by McCool *et al.* (1987). On the basis of these published results a value of 0.75 was used for 'n' and 1.45 for 'm' in deriving the WEI index.

The sampling points within each of the fields were located along transects. The location of each sampling point was selected to provide different positions along the slope that were representative of the geomorphic elements that could be distinguished within the fields. In general, the sampling points corresponded to the crest (a), midslope (b) and bottom of the slope (c). When the field length was short, only the crest and the bottom slope were sampled. In 16 of the studied fields, the slope length was long enough to clearly distinguish the crest, midslope and bottom slope and the sampling sites were respectively designated as a, b and c slope positions. In the remaining 12

fields with short slope length, only two slope positions were sampled, the crest and bottom slope (a and c slope positions).

The number of transects established in each field varied according to the field size and shape and the slope length. In general, sampling points along the transects were separated by about 30 m, leaving a distance from the lateral stone wall of around 10 m, while the distance from the top and bottom walls was between 5 and 10 m. Depending on the field shape (square or rectangular), individual fields generally had 6 sampling points (2 transects with 3 slope positions or 3 transects with 2 slope positions). Larger fields had 9 sampling sites (3 transects with 3 slope positions). Some of the fields included man-made features such as terraces constructed to prevent erosion, paths and channels. The sampling points avoided these features.

The soil sampling within a field was intended to represent the general condition of the entire soil surface within that field. Sampling of severely eroded patches or areas evidencing rilling was therefore specifically avoided, since in general these features were restricted to only small areas of some of the fields.

Whole core samples were collected using a motorised percussion corer equipped with an 8 cm core tube. In order to compare ^{137}Cs measurement between individual point samples and composite ones two types of samples were collected within each field: i) point samples that relate to a specific sample collected from a sampling point ii) composite samples, that represented a combination of several cores collected from the existing sampling points at each slope position. Each composite sample comprised 2-4 individual point samples.

The ^{137}Cs depth distribution was documented in selected fields, in order to characterize the depth distributions, found at the study site and to confirm the land use history of a specific field (see Ritchie & McHenry, 1973; Brown et al., 1981; Quine et

al., 1994). Fields abandoned before the main period of fallout in the late 1950s and early 1960s should be characterized by undisturbed ^{137}Cs profiles if no bioturbation processes occurred. In contrast, depth profiles showing evidence of vertical mixing should be found where a cultivated field was abandoned after the period of peak fallout. By excluding fields still in use and those recently abandoned (< 10 years before sampling), attention focussed on the remaining 16 fields. In these fields the ^{137}Cs depth distribution was documented by sectioning a core to provide depth incremental samples corresponding to 5 cm sections. To ensure that the entire ^{137}Cs profile was collected, the depth of sampling extended to between 30 and 60 cm. Where deposition might possibly have occurred, the sampling depth was increased.

In order to establish the local reference inventory for the study site, 9 small areas were identified as reference sites. These sites were located adjacent to the abandoned fields and were carefully selected to represent flat undisturbed locations, where neither erosion nor deposition would be expected to have occurred. At each reference site a soil profile was collected and depth incremental samples were taken up to 40 – 50 cm depth.

Sample preparation and analysis

The methodology for ^{137}Cs , Caesium-137, followed that commonly described in the literature (e.g. Wise, 1980; Walling & Quine, 1991). Samples were air-dried and ground to pass a 2mm sieve. The ^{137}Cs activity in a sample was measured using a high resolution, low background, low energy, hyperpure GE coaxial gamma-ray detector (EG&G ORTEC HPGe), coupled to an ORTEC amplifier and multichannel analyser. The gamma emission of ^{137}Cs at 661.6 keV was counted for 30000 s and the analytical precision of the measurements was approximately $\pm 6\%$ at the 95% level of confidence.

The minimum detectable activity for ^{137}Cs was 0.4 Bq kg^{-1} . The radioisotope activity is expressed as a concentration in Bq kg^{-1} . A total of 379 samples were analysed for ^{137}Cs activity. Of these, 187 were point samples, 72 composite samples, and 120 samples from sectioned cores that included reference inventory sites and the sites in the 16 fields where depth incremental samples were collected.

For each sample processed for ^{137}Cs measurement, the stone content ($\% > 2 \text{ mm}$) was recorded. The grain size composition of the $< 2 \text{ mm}$ fraction was determined by laser granulometry using Coulter equipment. Prior to measurement of grain size composition, all samples were heated with hydrogen peroxide to remove the organic fraction and then chemically dispersed using sodium hexametaphosphate. An ultrasonic probe was employed to ensure complete particle dispersion.

RESULTS AND DISCUSSION

The ^{137}Cs depth distribution.

The data from the 9 sampled reference sites were averaged to provide an estimate of the local reference inventory of $4500 \text{ Bqm}^{-2} \pm 204 \text{ Bqm}^{-2}$ at the 95% level of confidence. The coefficient of variation was 4.5 % and the allowable error (Mabit et al., 2012) was 3.5 % at the 95 % confidence level. Representative ^{137}Cs depth profiles from two of the reference sites are presented in Fig. 2. Both profiles exhibit the typical exponential decay of the radioisotope with depth, with the highest concentration occurring at the soil surface and almost no ^{137}Cs below the 35-40 cm soil depth. The ^{137}Cs depth distributions obtained for the 16 fields where depth incremental sampling was undertaken all conformed to expectations in terms of the land use histories reported by Molinillo et al. (1997)

All the fields that were abandoned more than thirty years previously were characterized by undisturbed (i.e. exponential) ^{137}Cs depth profiles. As found in other studies undertaken nearby in the Ebro Valley (Navas & Walling, 1992; Navas et al., 1997), the ^{137}Cs depth profiles provided evidence of erosion and aggradation at the midslope and bottom slope positions, respectively. Although there is some variability, a close relationship exists between the profile characteristics and their position along the slope.

In all the fields that were abandoned less than 30 years before sampling, ^{137}Cs was thoroughly mixed within the portion of the soil profile representing the plough layer. Again, evidence of erosion and aggradation at individual sampling points, was found according to their position on the slope. Further representative examples of ^{137}Cs depth profiles found in the study fields are presented in Fig. 2.

Soil redistribution indicated by ^{137}Cs

For the assessment of the patterns of soil redistribution, the spatial variation of ^{137}Cs activity along the transects in the study fields was investigated. The composite samples collected from the sampling points along the transects were representative of different slope positions which were in turn characteristic of the main physiographic elements of the slopes. This approach has already been successfully applied in other mountain environments within the region (Navas et al., 2005).

The distribution of ^{137}Cs along the slope transects is consistent with existing understanding of topographic controls on erosion and soil redistribution. Some depletion of ^{137}Cs inventories, relative to the reference inventory, occurs at the crests of the slopes, where the average inventory was 3920 Bqm^{-2} (sd=570). Sediment is

transported downslope and is deposited at the bottom of the slope, where ^{137}Cs inventories averaged 5320 Bqm^{-2} ($\text{sd} = 1020$). An analysis of variance test indicated that the mean inventories for the bottom of the slopes were significantly different from those for the crests and the midslopes, whereas differences between the latter were not significant (Fig. 3).

Similar results in terms of the pattern of soil redistribution were provided by the ^{137}Cs inventories associated with the point samples collected along the slope transects. The relationship between the ^{137}Cs inventory for individual sampling points and the equivalent values provided by composite samples was strong ($r = 0.92$, $p \leq 0.01$) and emphasises the close relationship between the ^{137}Cs inventories obtained from composite and point samples. This demonstrates that in this environment, data corresponding to a geomorphic element provided by composite samples can be used instead of point samples. Therefore, the number of ^{137}Cs analyses and the associated costs can be substantially reduced.

Because the peak of ^{137}Cs fallout occurred in 1963-1964, the group of fields included in the study were separated into two groups of 14 fields, based on the time of abandonment relative to the time of sampling. The two groups represented those fields abandoned for more than 30 years and those that had been abandoned less than 30 years previously. As can be seen in Fig. 4, the mean ^{137}Cs inventories for different positions along the slope transects derived from both composite and point samples were very similar. An analysis of variance test confirmed that the mean ^{137}Cs inventories of composite and point samples were not significantly different at the 95 % of confidence level. As expected, the general trend is an increase in the values of ^{137}Cs inventories from the crests to the bottom of the slopes.

In the fields with short slopes (where only the a and c positions were sampled), abandoned more than 30 years before sampling, the inventories are reduced by about 8% relative to the local reference inventory at crest positions, whereas they are increased by about 22% at the bottoms of the slopes. For the fields abandoned less than 30 years before sampling, the ^{137}Cs inventory has been reduced by about 12% at the crests, whereas it has increased by about 18% at the bottom of the slopes.

For the fields with long slopes (where a, b and c positions were sampled), in those abandoned more than 30 years before sampling, ^{137}Cs losses of ca. 12% and gains of ca. 15 %, relative to the local reference inventory, are associated with the slope crests and bottoms, respectively. These values are very similar to those documented for the fields with short slopes. For the fields abandoned less than 30 years before sampling, slightly lower inventories are found at midslope. Hence, in these longer fields, some erosion occurs at midslope and deposition at the bottom of the slopes is indicated by an increase in the inventory of around 23%. The key features observed in all the long fields is that sediment accumulates at the bottom of the slopes and that ^{137}Cs gains are slightly higher for the fields that were abandoned less than 30 years before sampling.

In the study fields significant ($p \leq 0.01$) negative relationships of the ^{137}Cs inventory with the clay fraction and with the clay plus silt fractions ($r = -0.369$; $r = -0.377$, respectively) were found. A direct relationship between the radionuclide activity and the clay content exist in soils, because ^{137}Cs is preferably attached to the fine soil fraction (Hird et al., 1996). Similar results were reported for sectioned cores collected along transects of cultivated and forest soils in a subhumid catchment in the Pre-Pyrenees (Gaspar & Navas, 2013). These negative relationships could reflect contrasts in the grain size composition of the soils found at the different slope positions due to soil redistribution processes. Furthermore, there is a coarsening of the soil at deposition

sites due to preferential deposition of the larger particles at the beginning of the bottom of the slopes where the sampling points are located. Information on the grain size composition of the soils is summarized in Table 2. The soils from crest and midslope positions have higher clay content and a lower sand content than soils from the bottom of the slope. Conversely the lowest clay contents are found at the bottom of the slope where the highest ^{137}Cs inventories and highest sand contents are found in relation to the accumulation of coarser particles at the beginning of the depositional area following a decreasing grain size pattern towards the bottom stone wall.

The effect of timing of land abandonment on soil redistribution

For the assessment if the timing of land abandonment had any effect on soil redistribution because of the differences in natural revegetation status and the conditions at the land abandonment, despite changes in rainfall erosivity with time could also had an effect, the study fields were subdivided into groups. If soil tillage and water erosion occurs, it is likely to result in an increased range in ^{137}Cs inventories, some areas will lose ^{137}Cs and some will gain by deposition because the fields are virtually closed systems. A total of six groups representing periods of increasing duration since abandonment with a 10 year increment was used, resulting in periods ranging between 0-10 years and 50->60 years. From this point on the periods are referred to by the last year of the period concerned before sampling (i.e. 20-30=30, 50->60=60). Fig. 5(a) presents information on the mean ^{137}Cs inventory and the percentage gain or loss of ^{137}Cs relative to the reference inventory, for each of the groups of fields with different periods of abandonment. The ^{137}Cs loss appears to be more intense in the fields abandoned more than 20 years before sampling, with an average reduction in the ^{137}Cs

inventory of 7%. On the contrary, the ^{137}Cs gain relative to the ^{137}Cs reference inventory is greatest for these fields. It appears that when average inventories for the individual fields are considered, age of abandonment has no significant impact on the average ^{137}Cs inventories of the study fields. Where low values of ^{137}Cs inventory are documented for midslope sampling points, these are commonly balanced by increased values of ^{137}Cs inventory at the bottom of the slope. For each slope position the means of the ^{137}Cs inventories have been compared amongst the 6 durations of land abandonment. The box and whisker plots for the mean ^{137}Cs inventory and the percentage gain or loss of ^{137}Cs for each slope position are presented in Fig. 5b. At the crest of the slope, all the fields exhibit some ^{137}Cs depletion. The highest ^{137}Cs losses occur both in the fields that were more recently abandoned (10 and 20 years before sampling) and in the fields abandoned 50 and 60 years before sampling. At the midslope no significant gain or loss of ^{137}Cs occurs. As an exception to this fact, the fields that were abandoned 30 years before sampling show ^{137}Cs losses of around 16 %. This can be interpreted as a combination of the timing of the field abandonment and the topographic conditions of the fields, because land abandonment left the soil surface unprotected at the time of ^{137}Cs peak fallout, and the midslope position is a part of the slope prone to erosion. In the fields that were abandoned 60 years before sampling ^{137}Cs gains at the midslope are around 16% and also exhibit the largest ^{137}Cs variability. The highest values of ^{137}Cs inventory appear, as expected, at the bottom of the slopes. On average, these values exceed 5300 Bqm^{-2} and reach maximum values of 7500 Bqm^{-2} in the fields abandoned 60 years before sampling. The increased inventory found in all the fields ranges between 3 % and 27 %. The minimum and maximum values of ^{137}Cs inventory occur in the fields abandoned 10 and 60 years before sampling. ^{137}Cs losses of -16 % and gain of + 56 % in relation to the ^{137}Cs reference inventory occur in the fields

abandoned 10 years before sampling and of -28 % and +70 % in the fields abandoned 60 years before sampling.

It appears that the highest ^{137}Cs losses and gains occur both in the recently abandoned fields and in the older abandoned ones. In the former fields, this could be interpreted as reflecting the known effect of cultivation on soil erosion, highlighted by several authors in different environments (e.g. Brown et al., 1981; Quine & Walling, 1991; Elliott & Cole-Clark, 1993). Therefore, inclusion of a longer period of cultivation in the time window over which ^{137}Cs measurements reflect soil redistribution is likely to result in greater soil redistribution and therefore greater increases and decreases in the ^{137}Cs inventory. As evidenced by the ^{137}Cs inventories in the fields recently abandoned (less than 10 years before sampling), the highest soil losses occur on the slope crest and soil is deposited at the bottom of the slope. The occurrence of a similar pattern in the fields abandoned more than 60 years before sampling could be explained by the successional changes in the vegetation associated with these fields. The disappearance of genista (*Genista scorpius*) after reaching a maximum coverage, as described by Montserrat (1990), would leave the soil surface unprotected against soil erosion and consequently could favour higher rates of soil redistribution.

Relationships of topographic factors with ^{137}Cs

It is widely documented that erosion increases as slope length and steepness increases (Wischmeier and Smith, 1978). Both slope length and steepness substantially affect sheet and rill erosion (Renard et al., 1997). A means to relate these factors to soil redistribution is to use the factors L and S in Eq. 1 from which a water erosion index (WEI) can be derived.

For the study fields, the range of ^{137}Cs inventories varies considerably. Because fields are surrounded by stone walls they function as virtually closed systems. Therefore, if water erosion occurs, it is likely to result in an increased range of ^{137}Cs inventories, as some areas will lose ^{137}Cs and some will gain by deposition.

If water erosion is the main driver of this increase in heterogeneity, then the increase in range of ^{137}Cs inventories could be expected to be proportional to the water erosion index. By using both linear relationships and reduced major axis functional relationships (RMA), as both variables are associated with error/uncertainty, (Webster, 1997) two groups are clearly differentiated (Fig.6). Both groups show a positive relationship between the water erosion index and the range of ^{137}Cs inventories, but they are characterised by different gradients in the relationships. Therefore, both groups show patterns consistent with water erosion induced increase in soil heterogeneity but at different intensities.

The correlation for the high range group is highly significant ($r = 0.969$, $p \leq 0.0001$) (excluding field number 8 which is an outlier that appears to be subject to even more intense erosion). A lower correlation coefficient ($r = 0.714$, $p \leq 0.001$) is obtained for the low range fields. This could be due to specific features of the fields in each of the groups, such as soil characteristics, aspect, land use or soil condition at the time of the abandonment. Moreover, the fields in the high range group are shorter. The average length is 46 m, whereas in the low range group the average length is 68 m. However, in the longer fields, it is common to find small manmade terraces and other structures that might affect soil redistribution either by trapping some sediment or by smoothing the slope, thus generating less soil erosion and eventually less soil redistribution in the whole field. As can be seen in Table 3, the percentage of manmade structures reaches 64 % of the total of the fields in the low range group, whereas it is only 30 % in the high

range group. Therefore, independently of the age of abandonment, the higher the water erosion index the larger the range of ^{137}Cs inventories, indicating higher intensity of soil redistribution. In the high range group the gradient is steeper than in the low range group, indicating a greater increase in heterogeneity for the same topographic state – i.e. more intense water erosion. Furthermore, by using the RMA relationships in Fig.6, estimates of the intensity of soil mobilization can be generated using data on the water erosion index.

CONCLUSIONS

In Mediterranean mountain environments it is possible to apply the ^{137}Cs technique to assess soil movement by using composite samples within the same geomorphic element, as similar results are obtained by analysing composite samples instead of point samples. Consequently, the number of suitable and representative samples can be smaller, and the financial costs notably reduced.

Land use has been found to be a key factor in controlling the depth distribution of the radioisotope. Patterns of sediment mobilization are strongly related to geomorphic elements within the slope fields. Tillage redistribution is important in many fields that show slightly reduced inventories at the top of a field, inventories similar to the reference inventory at midslope and increased inventories at the base of the slope.

Land use changes during the last decades also influence soil redistribution, since this is greater for recently abandoned fields, as well as for fields with the longest duration of abandonment, likely because of the increased period of cultivation in the former and the disappearance of vegetation cover in the latter. The natural revegetation in the study fields followed a series of successional changes in the vegetation cover of

which the disappearance of genista after reaching a maximum coverage is the main cause of leaving soil exposed in the older abandoned fields. These successional changes may also had an effect on the soil redistribution patterns. Over the soil redistribution caused by tillage while the fields were cultivated, after land abandonment runoff is a main factor of soil mobilization that further affected soil redistribution in the fields.

Using the relationships between the water erosion index and the range of ^{137}Cs inventories the intensity of the soil mobilization and redistribution can be assessed in mountain “wall bounded” fields although further research is needed to provide a definitive assessment of the effect of the time since land abandonment.

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Table 1. Summary of the characteristics of the studied fields.

field n°	land form elements *	n° of samples	field length m	slope °	years of abandonment
3	a	4	124	8.4	0
	c	4			
4	a	2	69	10.4	0
	b	2			
	c	2			
P1	a	4	64	10.3	0
	c	4			
P2	a	2	24	11.8	0
	b	2			
	c	2			
P3	a	2	66	14.7	0
	b	2			
	c	3			
P4	a	3	25	21.3	0
	c	3			
41	a	3	32	22.7	6
	c	3			
47	a	2	73	19.2	10
	b	2			
	c	1			
42	a	3	56	6.1	15
	c	3			
43	a	3	47	15.9	15
	c	3			
44	a	2	38	16.9	15
	c	3			
45	a	2	60	15.3	15
	b	2			
	c	3			
46	a	3	55	18.7	15
	b	2			
	c	3			
2A	a	3	80	16.0	20
	b	2			
	c	3			
7	a	2	31	17.8	31
	b	1			
	c	2			
15	a	2	70	16.5	31
	b	1			
	c	2			
16	a	2	74	21.0	31
	b	1			

	c	2			
21	a	3	98	16.9	32
	b	2			
	c	3			
10	a	3	60	11.6	33
	b	1			
	c	2			
11	a	1	82	17.7	33
	b	2			
	c	2			
48	a	2	73	25.7	33
	c	3			
8	a	2	47	14.4	35
	b	1			
	c	2			
49	a	3	63	30.1	42
	c	3			
50	a	2	61	27.0	42
	c	3			
52	a	3	43	28.2	50
	c	3			
17	a	2	71	21.2	60
	b	1			
	c	2			
18	a	2	65	15.8	70
	b	2			
	c	2			
51	a	3	33	25.9	70
	c	2			

* a = crest, b = midslope, c = footslope

Table 2. Basic statistics of the grain size fractions (%) at the different slope positions and multiple range test by applying the Fisher's least significance method at 95.0 percent.

	count	mean	minimum	maximum	variance	standard error
sand						
crest	25	20.1 a	9.7	32.3	33.0	1.1
midslope	10	19.1 a	10.8	24.2	21.4	1.8
bottom slope	27	24.0 b	13.6	41.4	34.4	1.1
silt						
crest	25	47.5 a	40.6	58.5	27.2	1.1
midslope	10	49.2 a	40.6	59.8	38.3	1.7
bottom slope	27	47.4 a	36.2	56.1	25.3	1.0
clay						
crest	25	32.3 a	24.4	41.7	23.3	0.8
midslope	10	31.8 a	27.3	39.2	14.4	1.3
bottom slope	27	28.6 b	22.5	37.8	12.0	0.8

Different letters are significantly different ($p \leq 0.05$)

Table 3.- Values of the WEI, and the ratio between the range ratio of ^{137}Cs inventories/WEI, the coefficient of variation for the high and low range groups of fields and the presence of manmade structures.

	Field number	Manmade structures	WEI	^{137}Cs range/WEI	CV %
high range	P2		1.1	116.7	54
	10	path	2.2	83.9	85
	4		2.1	92.6	89
	P4		2.9	75.8	108
	7		2.5	90.6	93
	45		3.3	76.1	103
	41	terrace	3.8	75.6	144
	51	terrace	4.8	59.8	145
	46		4.2	71.6	128
	17	terrace	6.2	56.3	149
low range	44		2.7	18.8	26
	42	terrace	3.4	19.4	33
	P1	terrace	1.9	34.7	33
	P3		3.3	20.7	28
	47		5.4	13.5	33
	3		2.3	36.2	42
	18	path	3.7	30.6	46
	52	terrace	6.8	16.9	57
	2A		4.7	28.8	51
	16	terrace	6.3	20.2	52
	43		2.9	46.9	68
	15	terrace	4.2	34.9	67
	50	terrace	8.2	18.2	75
	48	terrace	8.6	17.4	75
	11	path	5.2	30.4	73
	21	canal	5.5	29.1	66
	49	terrace	10.2	17.9	91

Figures

Figure 1. a) Location of the study area, b) topography and c) aerial photograph of the fields grouped by year of land abandonment.

Figure 2. Caesium 137 depth profiles in the study area. ^{137}Cs reference inventories at stable sites. Representative unploughed ^{137}Cs profiles found at sites that were abandoned more than 30 years ago. Ploughed ^{137}Cs profiles found at fields that were abandoned after the ^{137}Cs fallout, less than 30 years ago.

Figure 3. Box plots of ^{137}Cs inventories at the three slope positions, crest, talus and bottom slope for all the studied fields.

Figure 4. Distribution of ^{137}Cs inventories along the slope transects from composite and point samples in the fields abandoned less and more than 30 years before sampling.

Figure 5. a) Means of ^{137}Cs inventories and of the percentages of ^{137}Cs gained or lost with respect to the ^{137}Cs reference inventory. b) Box plots of ^{137}Cs inventories and of the percentages of ^{137}Cs gained or lost in each slope position: crest, midslope and bottom for each of the six periods of ten years each of land abandonment.

Figure 6. Relationships between the water erosion index (WEI) and the range of ^{137}Cs inventories by using the reduce major axis (RMA) and the lineal functions for the high and low range groups of fields.

Reference inventories

Undisturbed profiles

Ploughed profiles

----- 0% of ^{137}Cs gain/loss