Patterns of soil organic carbon and nitrogen in relation to soil movement under different land uses in mountain fields (South Central Pyrenees)

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Abstract

Cultivation on mountain landscapes has been identified as a main factor triggering soil erosion. Patterns of erosion, transport and deposition of soil particles in agricultural landscapes appears to be closely linked to that of soil nutrients. In this work the redistribution of soil organic carbon and nitrogen and of soil particles is analysed in different geomorphic parts of mountain fields. A southern orientated hillslope was selected as representative of main land uses in mountain farmland of the Central Spanish Pyrenees. In the region, as much as 74 % of its surface was abandoned in the last decades and as a result patterns of soil and nutrient losses in the fields were affected by both land abandonment and tillage. A set of cultivated and abandoned fields with different ages of land abandonment, slope gradients and lengths were selected to conduct this study. In each of the fields, total soil depth sampling was done in different parts of the slope to assess the pattern distribution of soil organic carbon (SOC) and nitrogen (SON). Other general soil properties analysed: pH, EC, carbonate content, grain size distribution and additional information derived from fallout caesium 137 provided supplementary information for better understanding the patterns of soil and nutrient redistribution. In the cultivated fields SOC and SON contents were higher and comparable to contents in the older abandoned fields, because the recovery of the natural vegetation after a long-term period of abandonment equalized the nutrient conditions in the cultivated fields that had regular additions of manure. In general SOC and SON percentages increased from the upper slope to the bottom slope of the fields with percentage increases ranging from 4 to 54 % and from 1.5 % to as much as 77 %, respectively. Similarly, significant increases of SOC and SON inventories (45 and 49 %, respectively) were registered at the bottom slopes of longer fields by comparison with lower increases (33 and 30 %, respectively) in shorter and steeper fields. Soil deposition at the bottom slope as indicated by the ^{137}Cs residuals was paralleled with increases in SOC and SON contents. Under the land use practices in the studied fields the bottom slope positions accumulate soil particles and act as sinks of soil carbon and nitrogen in these mountain agricultural landscapes.

Key words: SOC; SON; soil redistribution; nutrient sources and sinks; ^{137}Cs; mountain landscapes; agricultural fields; abandoned land; Central Spanish Pyrenees.

1. Introduction

In the Mediterranean region there is a concern on the set aside land process, as well as on the management of marginal lands especially in mountain landscapes that have been intensively cultivated for several centuries. The main traditional uses through farming and grazing triggered the clearance of natural forests. The process of transformation from forest to agricultural land caused increasing rates of soil erosion in the last millennium (Morellón et al., 2010). In addition, it is widely recognized that the loss of soil particles is often accompanied by depletion in soil nutrients with impacts on soil productivity.

Since Medieval times intensity of land uses has changed, thus in the Pyrenean mountains a great expansion of cultivated lands occurred at the end of the XIXth century and was followed by a process of land abandonment that started in the middle of the XXth century. The abandonment of marginal and non-productive lands occurred in successive pulses extending from the first part to the end of the XXth century. A main consequence of these rapid land use changes in the region was the increase in eroded surfaces that was paralleled with increases of sediment supplies to rivers and water bodies (Valero-Garcés et al., 1999; Navas et al., 2009). In mountain landscapes agricultural practices have been identified as main factors of soil loss (Navas et al., 2005a). In addition to erosion induced by tillage, the terrain physiography is another important factor affecting the soil redistribution and that of the nutrients in farmland landscapes (Ritchie and McCarty, 2008).

The reversal of the land abandonment process that starts with the plant colonisation may have some constraints linked to impoverishment in soil nutrients after centuries of intensive land use for the re-establishment of the vegetation (Brown, 1991). To recuperate abandoned and degraded lands in areas with high rainfall the natural recovery of the vegetation is a main option. However, little is known on the nutrient status of abandoned soils in mountain areas, though, this is a main issue as depletion of nutrient levels after intensive land use will condition the fertility of abandoned soils and the recovery of the natural vegetation (Navas et al., 2008).

Soil erosion involves preferential removal of the fine soil particles and of light fractions like soil organic carbon (Bajracharya et al., 2000) and is one of the major processes affecting the redistribution of soil organic carbon (SOC) and nitrogen (SON) in the landscapes (Lal, 2003). Soil erosion redistributes soil and SOC across agricultural landscapes (Zhang et al., 2006) and causes redeposition within the fields and net export (Ritchie and McCarty, 2003). Studies on spatial and temporal variation in SOC and SON are of great importance because of global environmental concerns. Agricultural practices affect the dynamics of SOC in soils (Quine and Van Oost, 2007; Van Oost et al., 2007), therefore understanding the mechanisms that control this dynamic is of interest to support sustainable agricultural practices and to promote the use of soils as carbon sinks to reduce the emissions of CO_2 (Lal 2004).

To assess soil erosion and redistribution fallout ^{137}Cs is being applied successfully in very diverse environments (e.g. Walling et al., 1999; Quine et al., 1994; Zhang et al., 2003, Martínez et al, 2009). In the region, studies by Navas et al. (1997, 2005a) used ^{137}Cs as soil radiotracer and evidenced the intense dynamics of the erosive/sedimentary process. The intensity of soil movement and its relationship with the process of land abandonment was assessed by McHenry et al. (1978) and Kachanoski (1987). For cultivated lands, several authors found clear links between soil redistribution processes and that of soil organic carbon evidenced by significant relationships between ^{137}Cs and SOC (Ritchie and McCarty, 2003; Li et al., 2006; Zhang et al., 2006; Ritchie et al., 2007). Therefore, fallout ^{137}Cs patterns could be used for assessing the dynamics of soil organic carbon and nitrogen on agricultural (Ritchie and McCarty, 2008, Wei et al., 2008) and also on rangeland landscapes (Martínez et al., 2010).

In the Aisa valley, that was most affected by land abandonment, a set of cultivated and abandoned small sized fields with different ages of abandonment, slope gradients and lengths were selected to assess variations in the contents of soil organic carbon and nitrogen .The distribution of these nutrients is analysed in different parts of the sloping fields together with that of grain size of soil particles and other general soil properties, namely pH, electrical conductivity and carbonate content. In addition, data on fallout ^{137}Cs from a previous research are used to assess the association between soil redistribution at the different slope positions and that of soil organic carbon and nitrogen. Identifying if ^{137}Cs and soil organic carbon and nitrogen have similar mechanisms of distribution in the landscape might allow association of the ^{137}Cs labelled areas of erosion or deposition with areas of depletion or enrichment of SOC and SON. Therefore, this work aims to assess if soil organic carbon and nitrogen derived from soil erosion at the upper positions of the slope results in the bury of amounts of SOC and SON at depositional sites at the bottom slope of the fields. Information derived from this research may help to identify sources and sinks of soil organic carbon and nitrogen and can be of interest to promote strategies for land conservation.

2. Material and Methods

The study was conducted on a south-facing slope of the Aisa valley (Central Spanish Pyrenees, Aragón) (Figure 1). In the valley altitudes range between 950 and 1400 m a.s.l. and traditional land uses are rainfed agriculture of cereal crops. The climate is sub Mediterranean type with Atlantic influence and mean annual precipitation of around 1000 mm. The major socioeconomic changes that favoured migration from rural to urban areas was especially intense in the Pyrenean valley of Aisa and according to Lasanta et al. (1995), the total percentage of abandoned land in this valley reached 74 %, one of the highest in the Pyrenees. The Calcaric Regosols are the main soil types developed on Eocene marls and sandstones at hisllslope positions. The soils originated from colluvial processes are poorly developed with almost no horizon differentiation and soil depth ranges between 30 to 60 cm. Soils have high carbonate percentages (35

%), alkaline pH and organic matter contents around 3 %. The natural vegetation on the southfacing slopes is composed of *Quercus gr. Faginea* and submediterranean shrubs.

The criteria for land abandonment were distance to the villages, orientation, slope gradient and size of the fields and occurred in different periods during the XXth century. A set of fields both still cultivated and abandoned were selected to conduct this study. For the abandoned fields further selection was done to cover the time span of the characteristic abandoning period in the past century (c.a. 60 years). Under the secular traditional private tenancy and management existing in the area the contour of the small sized fields are made of stone walls. A total of 24 fields with different lengths and slopes were selected (Table 1). Fields have irregular shapes and their size range between 0.1 and 1.5 has (Figure 1). In an attempt to analyse the effect of physiographic factors on the movement of nutrients and soil particles, the number of geomorphic elements that could be distinguished in each field was considered as a criteria for the groupment of the fields and they are named F2 and F3, respectively. In the F2 group (11 fields) two geomorphic positions were identified: upper slope and bottom slope. In the F3 group (13 fields) upper slope, midslope and bottom slope positions were identified. The F2 group is composed by steep (median: 21º slope) and short (median: 47 m) fields, apart from field 1, a long and gentle field included within the F2 group as the midslope element was not evident. F3 fields are longer (median: 66 m) and gentler (median: 16º) than F2 fields. A summary of the characteristics of the fields is presented in Table 1.

2.1 Soil sampling and analyses

In each field, the sampling sites were distributed along transects to represent the geomorphic elements corresponding to the upper slope, midslope and bottom slope positions. The length (m) and slope gradient (º) of the fields were measured to calculate the LS topographic factor of the RUSLE.

The number of sampling sites established in the fields varied depending on the size and shape of the field. In general, for characterizing each of the slope positions two rows were established for the F2 fields and three rows for the F3 fields. In each slope position the number of samples that were collected around 10 - 20 m apart varied depending on the size of the fields. Due to the irregular shape of the fields the number of samples collected ranged between 5 and 8 samples in larger fields, totalling 67 and 82 sampling sites in F2 and F3 fields, respectively (Table 1). The sampling depth was the total soil depth, 30 cm at the upper and midslope positions and 60 cm at the sites located at the bottom of the slope where soil particles have accumulated. The sampling depths were also established to retain the entire ^{137}Cs profile. After comparison with the reference inventory for the area it is possible to discriminate if soil loss or gain occurred and to relate it with the content and inventories of SOC and SON at a particular point. Whole core samples were collected using a 8 cm automatic core driller and composite samples were created from the proportional mixture of the point samples.

Samples were air-dried, ground, homogenized and quartered, to pass through a 2 mm sieve. From a total of 149 bulk samples collected a total of 56 composite samples were prepared for the analyses. Samples collected in each of the slope positions were merged to create a representative composite sample. Two and three composite samples representing the two and the three slope positions identified in the F2 and F3 fields, respectively, were analysed. Total organic carbon from the mineral soil (<2 mm) was determined by wet oxidation using a hot mixture of 1N potassium dichromate and concentrated sulphuric acid according to Guitian and Carballas (1976) using a titrimeter with selective electrode. Total nitrogen was measured using the Kjeldahl Method

(CSIC, 1976). The measures of SOC and SON are reported as concentration (%) and as content per surface area expressed as inventories or stocks (kg m^{-2}).

General soil properties pH, electrical conductivity (EC) and carbonate content were analysed following standard procedures. The pH (1:2.5 soil:water) was measured using a pH-meter. Electrical conductivity (dS m^{-1}) (1:5 soil:water) was measured using a conductivity meter. Carbonates were measured using a pressure calcimeter (CSIC, 1976). Analysis of sand, silt and clay were done by using laser equipment (Coulter LS 230). Samples were chemically disaggregated with sodium phosphate and then heated with hydrogen peroxide to guarantee total destruction of organic matter; ultrasounds were also applied to complete particle dispersion.

Estimates of the ^{137}Cs residuals were done from data of ^{137}Cs inventories in the composite samples from a previous research in the area (Navas et al., 1997). From the ^{137}Cs residuals (%), the amount of ^{137}Cs that is gained or lost by comparison with the reference inventory for the area (4500 ± 200 Bq m^{-2}, established from 9 stable sites) can be estimated. Because of the close association of the radioisotope with the fine fraction of the soil, the gain or loss of soil can be inferred. The methodology for Caesium-137 analyses is well described in the literature (Walling & Quine, 1991). Gamma emission of ^{137}Cs at 661.6 keV was counted for 30000 s (analytical precision of ± 8 %) by using a high resolution, low background, low energy, hyperpure Germanium coaxial detector coupled to an amplifier and multichannel analyser. The radioisotope content per surface area is expressed as inventories (Bq m^{-2}).

To assess the significance of the effects of the slope position in the fields F2 and F3 on SOC and SON at the sampling points we used an analysis of variance. To that end, the data were divided into F2 and F3 fields and into upper slope, midslope and bottom slope and α was set to 0.05. Correlations were established to assess the relationships between the length and slope of the fields, LS factor of the RUSLE with the SOC and SON contents. The effect of the variation of ^{137}Cs residuals on the SOC and SON contents and inventories was examined through linear regression analyses.

3. Results

In the studied fields, the results for all samples collected in fields F2 and F3 indicate that soils are alkaline with a mean pH of 8.22 (sd = 0.15) ranging between 7.73 and 8.49 (CV = 1.8 %). Salinity is very low, the mean value is 0.16 dSm^{-1} (sd= 0.08). The electrical conductivity is the soil property with highest variability and ranges between 0.1 and 0.74 dSm^{-1}(CV = 54 %). The carbonate content is relatively high with a mean of 36 % (sd = 8.2) and a range between 16 and 54 % (CV= 23 %).

The contents of soil organic carbon (SOC) and nitrogen (SON) in the composite samples for each of the studied fields are presented in Tables 2 and 3. The SOC percentages ($\overline{X}$ = 1.54 % ± 0.35) range between 0.91 and 3.09 % (CV = 22%) and the inventories ($\overline{X}$ = 5.08 kgm^{-2} ± 1.49) range between 2.8 and 12.8 kgm^{-2} (CV = 29%). The SON percentages ($\overline{X}$ = 0.16 % ± 0.03) range between 0.11 and 0.32 % (CV = 18 %) and the inventories ($\overline{X}$ = 0.54 kgm^{-2} ± 0.15) range between 0.32 and 1.32 kgm^{-2} (CV = 28 %). The mean of the ratio SOC/ SON is 9.4 (sd = 1.15) and varies between 7.4 and 12.8. No significant differences were found in the means of SOC and SON for the F2 and F3 fields. These contents are low but fall within the normal ranges for similar soils in the region (Navas et al., 2005 b). By comparison with mean values of 6.7 % found in similar natural soils under forest (López-Vicente and Navas, 2009) an important reduction of SOM levels was produced after the longterm and intense agricultural use in these fields. Depletion of the soil organic matter levels has been pointed out as a main constraint for the recovery of degraded soils. Exhaustion due to deforestation and continuous cropping of the fields may rend difficult the recovery of the natural vegetation in the region (Navas et al., 2008).

3.1. Lateral variation of SOC and SON

In the landscape, geomorphic processes acting on the slopes tend to regularize their profiles. As a result, a succession of geomorphic elements such as the crest at the upper part, the talus at the midslope position and the bottom slope at the lower part can be identified. Although the studied fields are contoured by stone walls a similar slope pattern is observed and for this reason SOC and SON along with the main soil properties are analysed separately for each slope position (Table 4).

Examination of the lateral distribution for all fields shows that contents of SOC and SON were greater at the bottom slope than at the upper slope with percentage increases ranging from 4 to 54 % for SOC and from 1.5 to 77 % for SON. The highest increase of SON was registered in a cultivated field that is regularly fertilized. At the upper slope positions, the mean percentages and inventories of SOC and SON are lower than at the midslope and bottom slope positions (Table 4). Mean SOC percentages and inventories increase around 7 % and 11 %, respectively, from the upper slope to the midslope and another 5 % and 20 %, respectively, increases at the bottom slope. In total, SOC increases by 40 % at the bottom slope where the highest SOC values are found. Similarly, mean SON percentages and inventories increase around 11% and 13 %, respectively, from the upper slope to the bottom slope.

In the fields, soil organic carbon and nitrogen are closely related and their variation follows a similar pattern as indicated by the direct and highly significant correlation between SOC and SON (Pearson r= 0.848, $p \leq 0.001$).

Concerning the general soil properties (Table 5) there is not a clear pattern in the variation of pH along the field slopes. Similarly, carbonate contents do not show a clear pattern because slightly higher values are found both at the upper and bottom slope than at the midslope position. However, the salinity as indicated by the values of EC decrease around 11 % from the upper slope to the bottom slope which may be due to leaching promoted by the accumulation of runoff at the lower part of the slope that together with its flatter topography facilitates infiltration and the leaching of the soil. The means of clay contents at the bottom slope (Table 5) are lower and significantly different from the other two slope positions ($p \leq 0.05$) suggesting that in spite of having contour stone walls some export of clays from the fields occurs with high runoff.

For all fields, an ANOVA test ($p \leq 0.05$) indicated no significant differences in the means of SOC (%) for each of the slope positions. A multiple range test (LSD Fisher) indicated that SON (%) means were lower and significantly different ($p \leq 0.05$) at the upper slope than at the bottom slope positions. However, the means of SOC and SON inventories (kg m^{-2}) were higher and significantly different ($p \leq 0.05$) at the bottom slope than at the other two slope positions. In catchment transects of Australia Martinez et al. (2010) found SOC content variations along hillslopes that were not related with the slope position.

Because of differences in the presence of a number of geomorphic elements in the fields, SOC and SON were examined separately for the two groups of fields (F2 and F3) in an attempt to relate their lateral variations with that of soil particles as indicated by the ^{137}Cs residuals. As shown in Figure 2 there is a general increase in the mean percentages and inventories of SOC and SON from the upper slope to the bottom slope positions which parallels the increases of ^{137}Cs inventories.

In the F3 fields increases of mean SOC percentages and inventories (12 % and 45%, respectively) are higher than in the F2 fields (10 % and 33%, respectively). Similarly, increases of mean SON percentages and inventories are of 16% and 49%, respectively in the F3 fields and of 7% and 30%, respectively, in the F2 fields. Within the F2 fields the means of percentages and inventories of SOC and SON differed significantly ($p \leq 0.05$) for the upper slope and bottom slope positions. In the F3 fields the means of SOC and SON inventories were higher and significantly different at the bottom slope than at the other two slope positions, but significant differences were not found for the means of SOC percentages.

The higher increases of SOC and SON at the bottom slope in F3 fields coincides with a mean ^{137}Cs gain of 18 % by comparison with a ^{137}Cs gain of 17 % in the F2 fields. In addition, clay percentages are also higher at the bottom slope of F3 fields (29.5 %) than at the bottom slope of F2 fields (26.8 %). Therefore, both higher ^{137}Cs gain and clay percentages explain the higher SOC and SON found at the bottom slope of F3 fields. The results are consistent with the fact that the length of the slope is related with higher erosion and this is consistent with the ^{137}Cs gain that indicates that the sites at the bottom slope had experienced deposition of soil particles and of the associated nutrients.

In addition to the significant differences ($p \leq 0.05$) in the means of the length and slope gradient for the F2 and F3 fields, the physiographic differences in the fields mainly the presence of a midslope element in the longer F3 fields agree with higher and significant ^{137}Cs gain ($p \leq 0.05$) that suggests a more intense redistribution of soil particles and of the associated nutrients in the F3 fields.

The existence of a midslope element that frequently coincides with manmade terraces, many of which have collapsed, also appears to intervene in the soil redistribution pattern. Thus, although in some cases field observations identified some deposition patches at the midslope it is also quite common to find bare soil and eroded surfaces. From the values of the ^{137}Cs residuals a mean ^{137}Cs loss of -6 % was estimated. Therefore, it appears that in general, the midslope elements function as source areas of sediments and contribute to the supply of soil particles that eventually accumulate at the bottom slope. In agreement with the regularization of slope profiles, fallout ^{137}Cs provided evidences of accumulation of soil particles at the bottom slope in different environments (e.g. Quine et al., 1994, Mabit et al., 2008). The processes operating on the geomorphic elements in the studied fields are sheet and rill erosion. Runoff triggers erosion then the subsequent transport of soil particles and nutrients take place along the slope and finally they accumulate at the lower end of the fields.

The effect of topographic factors on the nutrient contents was examined through correlations established between topographic factors and the SOC and SON percentages and inventories (Table 6). For the F3 fields ($p \leq 0:05$), decreasing SOC and SON contents for increasing slope values suggested that conditions of higher slope gradient favoured the loss of nutrients. Decreasing SON contents are also observed for increasing slope values ($p \leq 0:05$) in the F2 fields. This trend would agree with the fact that higher erosion occurs on steeper slopes (Morgan, 1995).

The lower levels of SOC and SON found at the upper slope positions of the fields, is coincidental with a loss of ^{137}Cs (-16 % for the F2, -8 % for the F3 fields). Navas et al. (1997) found in this area a general and statistically significant increase of ^{137}Cs inventories from the upper slope to the bottom slope positions that indicated accumulation of soil particles at the lower parts of the slope. Organic matter is preferentially removed from the eroded soil, thereby depleting the contents of SOC at the erosion source. This can explain the relatively lower levels of SOC and SON at the upper slope positions of the fields where field observations also identified some eroding patches. At the bottom of the slope there is a gain of ^{137}Cs that suggests deposition of soil particles that remain trapped at the lower end of the fields. As a consequence SOC and SON percentages and inventories are highest at the bottom slope positions.

The relationships between the ^{137}Cs residuals, that are expressed as percentage of the ^{137}Cs gained or lost and the percentages and inventories of SOC and SON, with stronger correlations for SOC and SON inventories, indicate that the levels of nutrients increase for increasing percentages of ^{137}Cs gain (Table 6). The statistically significant relationships ($p \leq 0.05$) for the F2 and F3 fields, with the SOC and SON inventories, and also with SOC and SON percentages for the F3 fields confirm that a gain of ^{137}Cs and therefore of soil particles is paralleled with a gain in SOC and SON (Figure 3). According to Lal (2003) eroded sediments are enriched in organic matter in a ratio greater than 1 because organic matter concentrates in the topsoil and is preferentially removed by runoff. Martinez et al. (2010) also found strong and significant relationships between ^{137}Cs and SOC for previously cultivated creak flats in a region of Australia. However, the relationships between ^{137}Cs residuals and SOC and SON percentages are not statistically significant for the F2 fields which might be due to a lower number of observations and to the more limited soil redistribution within these fields in comparison with the F3 fields.

In the F3 fields although the relationships between clay percentages and SOC and SON percentages and inventories were not significant they showed the expected direct trend (Table 6). This was not the case for the F2 fields and could be also the reason for the lack of significance in the relationships of SOC and SON percentages with the ^{137}Cs residuals. The lack of significance in the relationships between clay and SOC and SON that show a negative trend could be due to some export of the finest soil fraction with high runoff events which might trespass the stone walls. Also enrichment in sand contents at bottom slopes is associated with selective deposition of coarser particles at accumulation sites. In addition, because, F3 fields are longer they are more likely to trap clays inside the fields than in the shorter and steeper F2 fields.

At the bottom slope positions, general increases in SOC and SON inventories exceeded 40 % in F3 fields and 30% in F2 fields, although increases of SOC and SON percentages were more moderate. In the nutrient dynamics it has to be considered that part of the eroded SOC and SON deposited at the bottom slope of the fields can be mineralized. Jacinthe and Lal (2001) indicated that as much as 20–30% of the displaced soil organic carbon may be emitted into the atmosphere. The light fractions transported by runoff are labile and can be easily mineralized (Lal, 2003). When the nutrients are buried they become protected and they are less mineralizable than in the soil from which it is derived (Stallard, 1998). Furthermore, if some export of clays is likely to have occurred in these fields and because the close association of nutrients with the fine particles of the soil (Lal, 2003), some export of nutrients from the fields may have also occurred.

In the sloping fields the geomorphic position determines the areas of erosion which are the source of soil particles and of deposition where soil accumulates. Following this scheme, patterns of soil erosion and of subsequent redistribution of soil particles appear to be closely linked to that of carbon and nitrogen in soils. Mabit et al. (2008) also found a significant relationship between soil ^{137}Cs and soil organic matter and suggest that erosion would explain the variability of SOM in cultivated fields.

The homogeneity of the studied fields that have similar soil types, parent materials and slope orientation can be the reason for the similar behaviour of SOC and SON. Their accumulation at the lower parts of the fields in close link with that of soil reflects that topography was a key factor affecting the pattern of the lateral distribution of SOC and SON. Ritchie and McCarty (2008) and Martinez et al. (2010) also found strong links between soil redistribution and soil organic carbon concentrations suggesting that they move along similar physical pathways in agricultural soils.

3.2. Temporal evolution of SOC and SON after land abandonment

To assess the variations of SOC and SON percentages for the different periods of land abandonment and to compare with conditions in the fields that are still in use, the studied fields were grouped in periods of 10 years of land abandonment. A total of 6 groups, each corresponding to a period of 10 years, from present to more than 60 years of abandonment was established (Figure 4).

An analysis of variance in function of the age of abandonment was performed for SOC and SON and the results indicated statistically significant differences at the 95% confidence level between the means of the nutrients in function of the age of abandonment for each of the 10 year period groups. However, differences can not be related with soil movement in the fields as results of an ANOVA for the ^{137}Cs inventories in function of the age of abandonment did not show statistically significant differences for the ^{137}Cs inventory means in each of the 10 year period groups.

The box and whisker plots in Figure 4 shows that SOC was highest in the fields that are in use and that their means are not significantly different from mean SOC percentages in fields abandoned 40, 50 and 60 years ago. However, mean SOC percentages differed significantly from the means in fields abandoned 10, 20 and 30 years ago. The reason could be that fields that are cultivated are fertilized regularly with manure and therefore SOC contents are high. Then, after land abandonment a depletion period follows until the decreasing trend is reversed when the recovery of the natural vegetation is substantial enough as to incorporate organic matter in the natural plant-soil cycle. The SOC percentages start increasing after 30 years of abandonment and after more than 60 years of abandonment SOC reaches similar contents as those found in the cultivated fields that are fertilized. Total nitrogen also had highest mean values in the fields that are still in use and they were significantly different from the means of the rest of the fields, apart from the 10 and 40 years abandoned fields. However mean SON values for the longest periods of abandonment did not reach the contents in the fields in use. The ratio SOC/SON had the lowest values for the more recently abandoned fields (10 and 20 years) and differed significantly from the older fields (50 and 60 years). With time, there is trend to reach the equilibrium and the values closer to the optimum value of this ratio (10) were found in the oldest fields that are only comparable to the high ratio found in the cultivated fields that are fertilized regularly.

For the other soil properties some variations were found in function of the time of land abandonment (Figure 5). The pH means tend to increase for longer periods of land abandonment, and the highest values were found in the fields abandoned 50 and 60 years ago. The contrary was observed for the EC means that progressively decreased for increasing periods of land abandonment with the EC lowest values in fields abandoned 50 years ago. The reason of the EC trend can be explained because after land abandonment the addition of fertilizers ceased and as a consequence of leaching salinity is reduced with time. The means of carbonate contents do not follow this pattern as contents increased since the onset of land abandonment till the 20 years period of land abandonment. However, the variation in carbonate content is likely to be associated with the grain size distribution because silt is the fraction more abundant in the soils (around 50 %) and silt material is of carbonatic nature. As can be seen in Figure 5 the means of silt content increased for the same period and then slightly decreased for longer periods of land abandonment. The opposite pattern was found for the sand contents. The means of clay percentages indicated a trend to decrease for longer time of land abandonment since the 30 years period of abandonment. The relatively low clay contents in the oldest fields may be the reason for the moderate SOC and SON increases observed in these fields. In addition, in the oldest fields the successional changes that had occurred in the vegetation led to the total disappearance of *Genista scorpius* produced after reaching a maximum development (Montserrat, 1990). This may also contribute to explain the relatively low increases of SOC and SON in the oldest fields.

The natural evolution of the soil since the onset of the land abandonment process may result in different contents of nutrients depending on the conditions at the moment of land abandonment as well as on the natural process of vegetation recovery.

4. Conclusions

In the fields, the redistribution patterns of soil nutrients are closely linked to that of soil particles. The mobilization of soil carbon and nitrogen occurs in association with the fine soil fraction induced by water erosion and following the expected pattern along the slope from the upper part to the bottom slope. The movement of soil particles and associated nutrients is affected by topographic factors such as the length and slope gradient. Larger redistribution of soil particles and of soil organic carbon and nitrogen are more likely to occur in long and steep fields with high values of the topographic LS factor of the RUSLE.

The contents of SOC and SON are directly related. Increases of SOC from the upper slope to the bottom slope are paralleled with increases of SON. Soil deposition at the bottom slope as shown by fallout ^{137}Cs inventories is paralleled with increases in SOC and SON contents. Less common SOC decreases occur in some sites at the bottom of the slope with no evidence of soil deposition therefore, SOC depletion is associated to loss of fine soil particles.

The upper and midslope positions are the source areas of soil particles as indicated by ^{137}Cs and nutrients that are transported downslope accumulate at the bottom positions where soil organic carbon and nitrogen are buried. Substantial increases of SOC and SON by compared with inventories at the source areas indicate that bottom slopes of the contoured fields are effective sinks of SOC and SON.

Contents of SOC and SON varied in function of the land use and the period of abandonment of the fields. In cultivated and old abandoned fields SOC and SON were higher and comparable. Initial conditions of the fields at the time of abandonment and effects of the plant succession along the years may have resulted in different processes affecting the contents of soil organic carbon and nitrogen. The dynamic of the nutrients after land abandonment may have followed different patterns that eventually had resulted in different contents and ranges for the different periods of land abandonment.

Relationships between nutrients and ^{137}Cs evidenced that SOC, SON and the radiosiotope are affected by similar physical processes and are likewise redistributed downslope. The fallout ^{137}Cs provided consistent information to trace the soil movement and that of the associated soil nutrients and is a valuable tool to identify sources and sinks of soil organic carbon and nitrogen in rapidly changing environments as the Mediterranean mountains.

Results from this study may help to improve the knowledge on the fate of nutrients (SOC and SON) that are redistributed by erosional and tillage processes which are not still completely understood. Information gained from this research can be of interest to establish criteria on conditions for land abandonment in order to minimize the impacts on both soil and nutrient losses.

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Figures

Fig. 1. Location of the study area in the central part of the Spanish Pyrenees, aerial photograph of the studied fields and view of the contoured abandoned and cultivated fields in the Aisa valley.

Fig. 2. Mean values of SOC and SON percentages and inventories and mean ^{137}Cs inventories at the different slope positions in the F2 and F3 fields.

Fig. 3. Relationships between the percentages of ^{137}Cs gained or lost and the percentages and inventories of SOC and SON in the F2 and F3 fields (* $p \leq 0.05$).

Fig. 4. Box plots of SOC and SON percentages and of the ratio SOC/SON in the fields still in use and in the abandoned fields with different periods of land abandonment.

Fig. 5. Box plots of pH, EC and of carbonate, sand, silt and clay contents in the fields still in use and in the abandoned fields with different periods of land abandonment.

Table 1. Summary data of the fields with two (F2) and three (F3) geomorphic positions along the slope in the Aisa valley.

F2						F3					
field	n	length m	slope º	LS	y	field	n	length m	slope º	LS	y
1	8	124.0	8.37	1037.9	0	1	6	69.0	10.42	719.0	0
2	8	64.0	10.32	660.5	0	2	6	24.0	11.78	282.7	0
3	6	25.0	21.32	533.0	0	3	7	66.0	14.73	972.2	0
4	6	32.0	22.72	727.0	6	4	5	73.0	19.19	1400.9	10
5	6	56.0	16.05	898.8	15	5	7	60.0	15.31	918.6	15
6	6	47.0	15.85	745.0	15	6	8	55.0	18.72	1029.6	15
7	5	38.0	16.85	640.3	15	7	8	80.0	15.98	1278.4	20
8	5	73.0	25.67	1873.9	33	8	5	31.0	17.76	550.6	31
9	6	63.5	30.10	1911.4	42	9	5	70.5	16.48	1161.8	31
10	6	43.0	28.18	1211.7	50	10	5	74.0	20.95	1550.3	31
11	5	33.0	25.92	855.4	70	11	8	98.5	16.88	1662.7	32
						12	6	60.0	11.63	697.8	33
						13	6	65.0	15.78	1025.7	70

LS = length (m) * slope (º)
n sampling sites.
y years of abandonment.

Table 2. Means of SOC, SON, SOC/SON ratio, grain size percentages and ^{137}Cs inventories in the F2 fields of the Aisa valley.

field	n	SOC %		SOC kg m^{-2}		SON %		SON kg m^{-2}		SOC/SON		sand %		silt %		clay %		^{137}Cs Bq m^{-2}	
F2		mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
1	8	1.52	0.11	5.37	0.64	0.17	0.00	0.59	0.02	9.10	0.85	36.2	7.4	38.6	3.5	25.3	3.9	4643.5	591.4
2	8	1.57	0.09	5.04	0.98	0.17	0.01	0.54	0.11	9.30	0.00	25.2	4.0	45.5	0.7	29.2	4.7	3427.3	469.6
3	6	1.37	0.05	4.73	1.04	0.15	0.00	0.51	0.10	9.20	0.28	24.6	9.9	41.7	4.7	33.7	5.2	4058.7	1531.0
4	6	1.42	0.16	4.71	1.59	0.16	0.01	0.54	0.16	8.75	0.35	16.7	1.0	51.1	0.0	32.2	1.1	5581.5	2035.0
5	6	1.27	0.03	4.43	1.03	0.15	0.01	0.54	0.19	8.30	0.99	17.1	0.6	54.1	1.4	28.8	0.8	4162.9	462.2
6	6	1.27	0.03	4.55	1.04	0.17	0.01	0.60	0.16	7.65	0.35	21.1	2.4	52.1	0.4	26.7	2.8	4464.5	958.7
7	5	1.31	0.06	4.85	1.44	0.15	0.01	0.54	0.11	8.85	0.78	17.9	7.5	54.6	5.6	27.6	1.9	4430.1	360.0
8	5	1.59	0.02	4.70	0.90	0.17	0.01	0.49	0.14	9.70	0.85	19.6	7.5	46.3	2.2	34.1	9.7	3730.2	1063.9
9	6	1.51	0.16	5.21	0.79	0.15	0.02	0.51	0.08	10.10	0.00	26.3	8.4	45.1	5.7	28.6	2.7	5047.3	1293.0
10	6	1.46	0.26	5.08	1.20	0.14	0.02	0.50	0.09	10.05	0.64	24.8	7.6	46.6	4.3	28.7	3.3	3855.9	809.5
11	5	1.51	0.24	4.99	1.77	0.14	0.01	0.46	0.11	10.70	1.27	30.5	2.6	44.4	3.9	25.1	1.3	6209.6	2043.8

sd standard deviation.

n number of samples collected.

Table 3. Means of SOC, SON, SOC/SON ratio, grain size percentages and ^{137}Cs inventories in the F3 fields of the Aisa valley.

field	n	SOC %		SOC kg m^{-2}		SON %		SON kg m^{-2}		SOC/SON		sand %		silt %		clay %		^{137}Cs Bq m^{-2}	
F3		mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
1	6	2.47	0.55	7.99	4.20	0.24	0.07	0.78	0.47	10.70	1.82	20.2	1.8	48.8	2.5	31.0	2.1	4803.3	1086.4
2	6	1.78	0.15	6.36	0.65	0.18	0.03	0.64	0.13	10.07	1.33	21.9	2.4	42.3	1.5	35.8	3.4	5106.4	657.7
3	7	1.65	0.15	5.12	0.44	0.19	0.03	0.57	0.07	8.97	1.10	25.4	4.7	45.4	2.5	29.2	4.5	5019.0	346.1
4	5	1.43	0.31	5.22	1.74	0.17	0.02	0.60	0.15	8.53	0.99	20.3	6.0	48.0	5.4	31.7	3.5	4458.9	229.4
5	7	1.33	0.37	5.32	1.22	0.15	0.02	0.60	0.05	8.80	1.35	14.5	4.7	54.8	2.3	30.7	2.6	4812.0	1256.9
6	8	1.44	0.24	4.33	1.74	0.15	0.02	0.43	0.13	9.87	1.06	20.0	8.2	54.2	6.7	25.7	1.4	4716.0	1571.8
7	8	1.14	0.21	4.07	1.07	0.13	0.01	0.46	0.11	8.83	0.72	20.8	4.6	51.4	3.4	27.8	1.1	4296.2	628.7
8	5	1.33	0.24	4.11	1.21	0.15	0.02	0.46	0.10	8.95	0.64	16.5	9.6	51.4	6.0	32.1	3.6	4786.0	1141.6
9	5	1.80	0.37	5.50	0.11	0.16	0.00	0.51	0.12	11.05	2.47	16.3	3.9	47.1	3.1	36.7	7.0	4345.0	814.3
10	5	1.79	0.28	4.47	0.21	0.17	0.03	0.43	0.02	10.40	0.14	18.6	1.9	44.7	5.0	36.7	6.9	4223.5	639.5
11	8	1.45	0.39	4.84	2.84	0.16	0.03	0.52	0.27	9.10	0.71	22.9	2.7	44.0	0.5	33.1	2.1	4227.2	808.4
12	6	1.50	0.06	5.01	1.58	0.17	0.01	0.57	0.19	8.90	0.14	21.7	2.2	48.1	2.7	30.2	0.5	4541.2	1044.2
13	6	1.71	0.23	4.71	0.39	0.17	0.02	0.46	0.07	10.27	0.58	23.7	4.4	47.0	7.6	29.3	4.2	3833.3	563.3

sd standard deviation.
n number of samples collected.

Table 4. Basic statistics of SOC, SON and of the ratio SOC/SON in the different slope positions of the studied fields in the Aisa valley.

	n	mean		median	sd	CV %	min	max
upper slope								
SOC %	24	1.45	a	1.37	0.33	22.8	0.91	2.28
SOC kg m^{-2}	24	4.28	a	4.03	0.89	20.8	2.83	5.90
SON %	24	0.15	a	0.15	0.02	13.4	0.11	0.21
SON kg m^{-2}	24	0.45	a	0.44	0.07	15.9	0.33	0.64
SOC/SON	24	9.43	a	9.00	1.42	15.1	7.40	12.80
midslope								
SOC %	8	1.54	a	1.58	0.35	22.6	1.10	2.05
SOC kg m^{-2}	8	4.77	a	4.82	1.09	22.9	3.09	6.07
SON %	8	0.16	ab	0.16	0.03	18.7	0.13	0.21
SON kg m^{-2}	8	0.51	a	0.54	0.13	24.7	0.32	0.65
SOC/SON	8	9.42	a	9.46	0.92	9.7	7.46	10.58
bottom slope								
SOC %	24	1.62	a	1.58	0.35	21.6	1.25	3.09
SOC kg m^{-2}	24	5.99	b	5.77	1.62	27.1	4.32	12.83
SON %	24	0.17	b	0.17	0.03	20.2	0.14	0.32
SON kg m^{-2}	24	0.64	b	0.60	0.17	26.2	0.42	1.32
SOC/SON	24	9.44	a	9.38	0.94	10.0	7.40	11.55

sd standard deviation.
CV coefficient of variation.
Different letters indicate significant differences $p \leq 0.05$.

Table 5. Basic statistics of pH, electrical conductivity, carbonate and clay contents in the different slope positions of the studied fields in the Aisa valley.

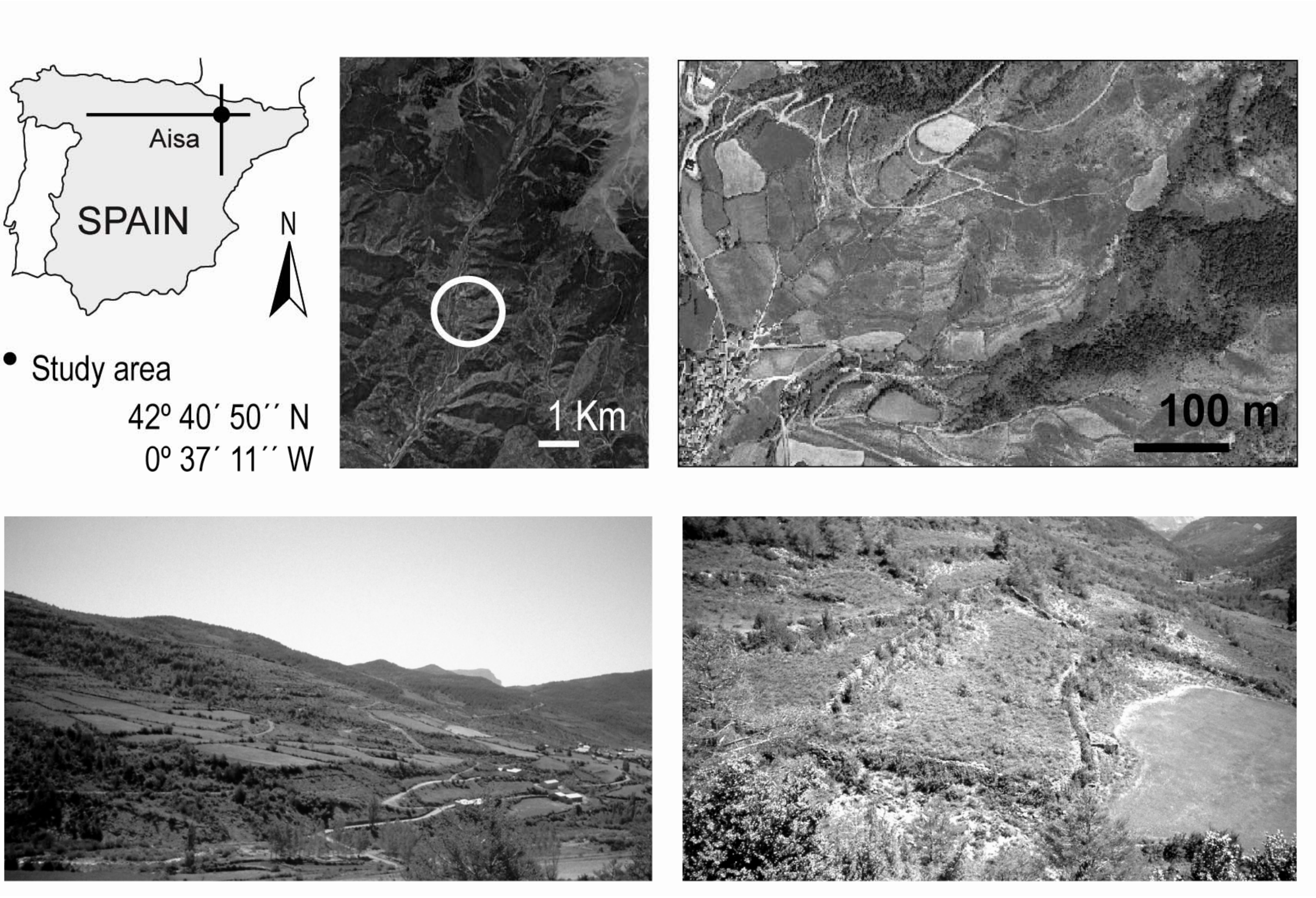
	n	mean		median	sd	CV %	min	max
upper slope								
pH	24	8.24	a	8.29	0.17	2.1	7.73	8.49
EC dSm^{-1}	24	0.17	a	0.13	0.12	75.4	0.10	0.74
$CO_3^{=}$ %	24	36.56	a	38.58	9.35	25.6	16.36	53.78
clay %	24	32.07	a	30.83	4.77	14.9	24.43	41.66
midslope								
pH	8	8.18	a	8.19	0.13	1.5	7.97	8.33
EC dSm^{-1}	8	0.16	a	0.15	0.03	20.1	0.13	0.21
$CO_3^{=}$ %	8	31.65	a	34.46	9.16	28.9	17.41	41.89
clay %	8	31.77	a	31.14	4.09	12.9	27.25	39.18
bottom slope								
pH	24	8.20	a	8.26	0.13	1.6	7.93	8.37
EC dSm^{-1}	24	0.15	a	0.13	0.03	18.8	0.11	0.21
$CO_3^{=}$ %	24	37.21	a	38.40	6.27	16.8	24.16	46.23
clay %	24	28.23	b	27.62	3.11	11.0	22.48	33.10

sd standard deviation.
CV coefficient of variation.
Different letters indicate significant differences $p \leq 0.05$.

Table 6. Pearson correlation coefficients between SOC, SON, clays, ^{137}Cs and topographic factors.

	SOC %	SOC kg m^{-2}	SON %	SON kg m^{-2}	SOC/SON	clay %	^{137}Cs % residual	length m	slope °	LS
all fields										
SOC %		**0.767**	**0.844**	**0.561**	**0.582**	0.260	**0.320**	0.083	-0.238	-0.090
SOC kg m^{-2}			**0.764**	**0.920**	**0.275**	0.027	**0.546**	0.015	-0.220	-0.156
SON %				**0.770**	0.058	0.169	**0.313**	0.101	**-0.359**	-0.167
SON kg m^{-2}					-0.116	-0.046	**0.497**	0.025	**-0.284**	-0.196
SOC/SON						0.210	0.160	-0.021	0.118	0.076
clay %							**-0.330**	-0.105	0.003	0.025
^{137}Cs % residual								-0.177	0.061	-0.144
length m									**-0.288**	**0.600**
slope °										**0.532**
F2 fields										
SOC %		**0.553**	0.359	0.127	**0.706**	-0.146	0.370	0.327	0.152	0.404
SOC kg m^{-2}			0.295	**0.803**	0.345	**-0.489**	**0.574**	0.161	0.000	0.090
SON %				**0.566**	-0.405	-0.161	0.141	**0.434**	**-0.477**	-0.003
SON kg m^{-2}					-0.276	**-0.464**	**0.416**	0.177	-0.307	-0.130
SOC/SON						-0.040	0.289	-0.016	**0.519**	0.396
clay %							**-0.528**	-0.208	0.224	0.116
^{137}Cs % residual								-0.146	0.214	-0.036
length m									**-0.477**	0.395
slope °										**0.557**
F3 fields										
SOC %		**0.796**	**0.876**	**0.625**	**0.575**	0.319	**0.377**	-0.049	**-0.429**	-0.249
SOC kg m^{-2}			**0.819**	**0.942**	0.249	0.156	**0.620**	-0.086	**-0.439**	-0.272
SON %				**0.808**	0.113	0.207	**0.437**	-0.035	**-0.441**	-0.246
SON kg m^{-2}					-0.086	0.073	**0.606**	-0.066	**-0.412**	-0.244
SOC/SON						0.298	0.072	-0.076	-0.137	-0.119
clay %							-0.207	-0.119	-0.024	-0.042
^{137}Cs % residual								-0.245	-0.171	-0.262
length m									0.281	**0.871**
slope °										**0.698**

Bold face numbers are significant at $p \leq 0.05$.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N
Study area
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0º 37´ 11´´ W
1 Km
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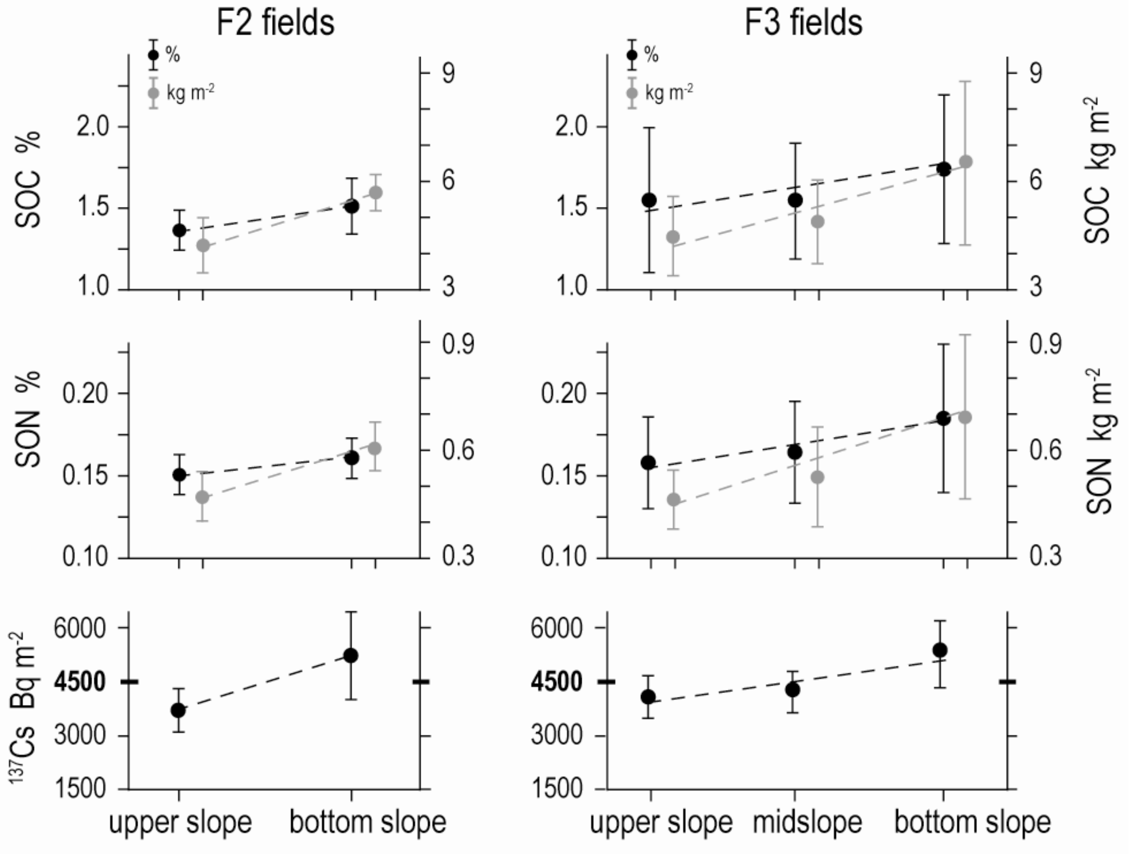
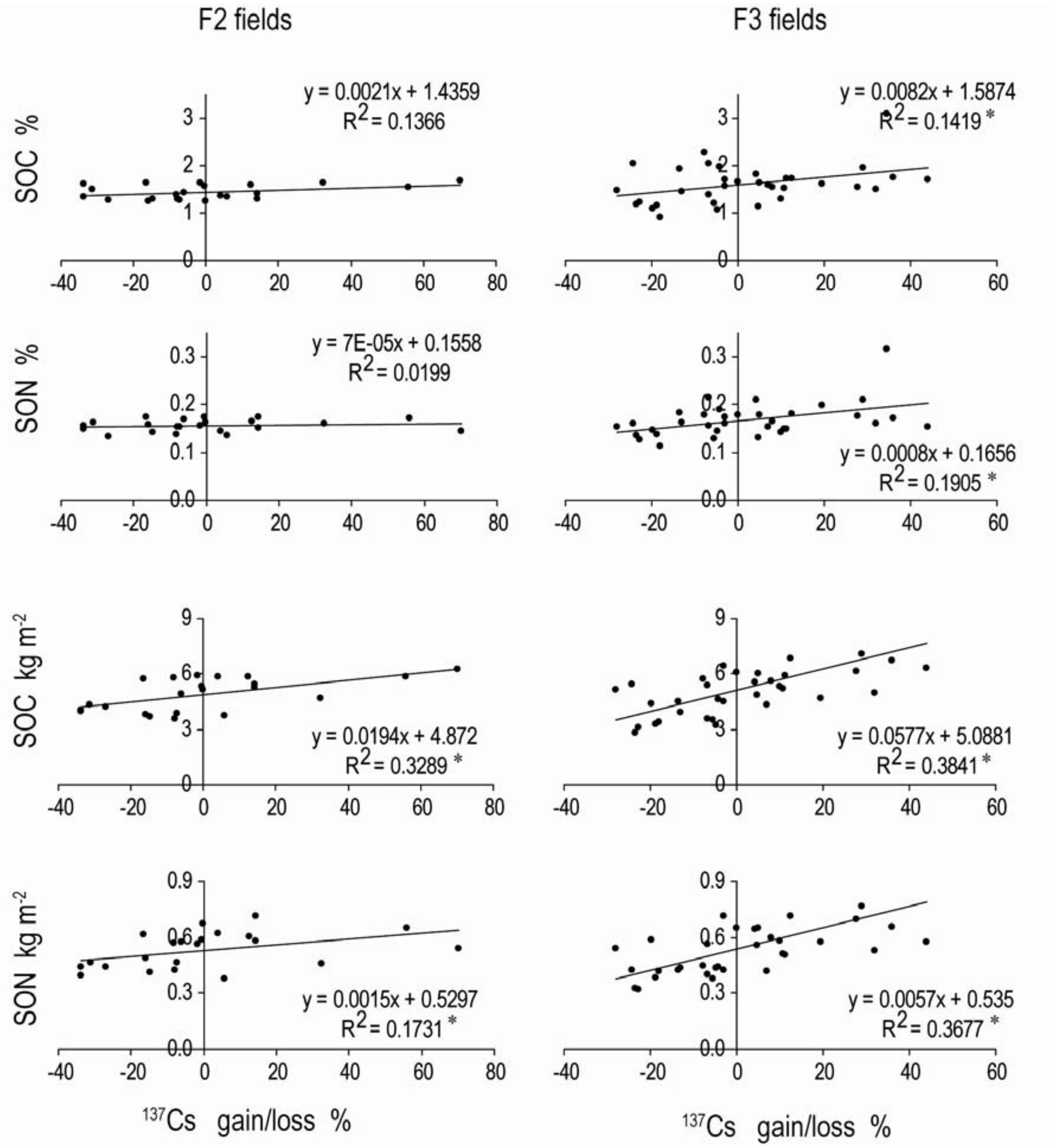

F2 fields
F3 fields
%
kg m-2
SOC %
SOC kg m-2
2.0
1.5
1.0
9
6
3
SON %
SON kg m-2
0.20
0.15
0.10
0.9
0.6
0.3
137Cs Bq m-2
6000
4500
3000
1500
upper slope
midslope
bottom slope


F2 fields
F3 fields
SOC %
SON %
SOC kg m^{-2}
SON kg m^{-2}
y = 0.0021x + 1.4359
R^2 = 0.1366
y = 0.0082x + 1.5874
R^2 = 0.1419 *
y = 7E-05x + 0.1558
R^2 = 0.0199
y = 0.0008x + 0.1656
R^2 = 0.1905 *
y = 0.0194x + 4.872
R^2 = 0.3289 *
y = 0.0577x + 5.0881
R^2 = 0.3841 *
y = 0.0015x + 0.5297
R^2 = 0.1731 *
y = 0.0057x + 0.535
R^2 = 0.3677 *
0
1
2
3
0.0
0.1
0.2
0.3
0
3
6
9
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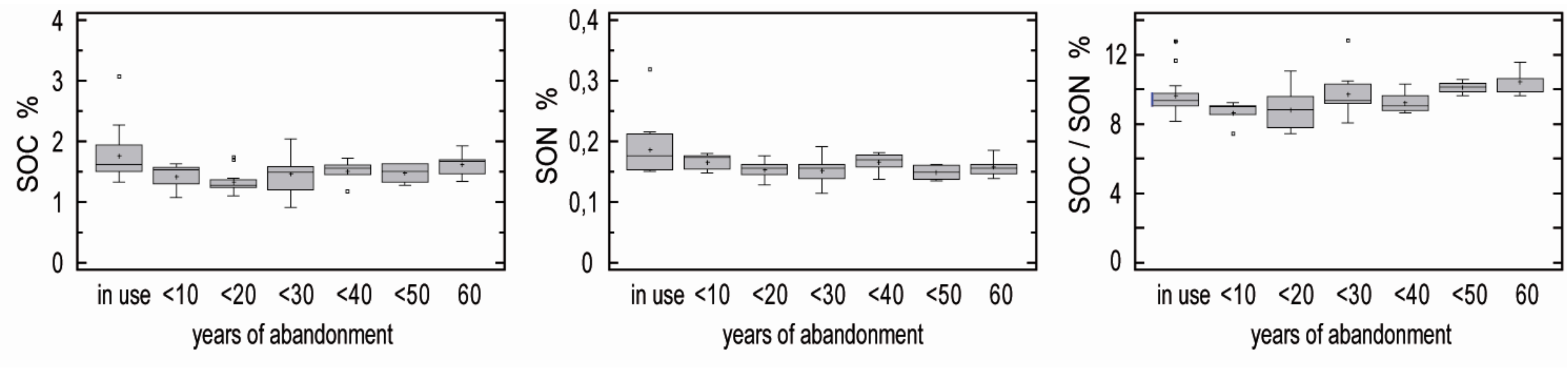
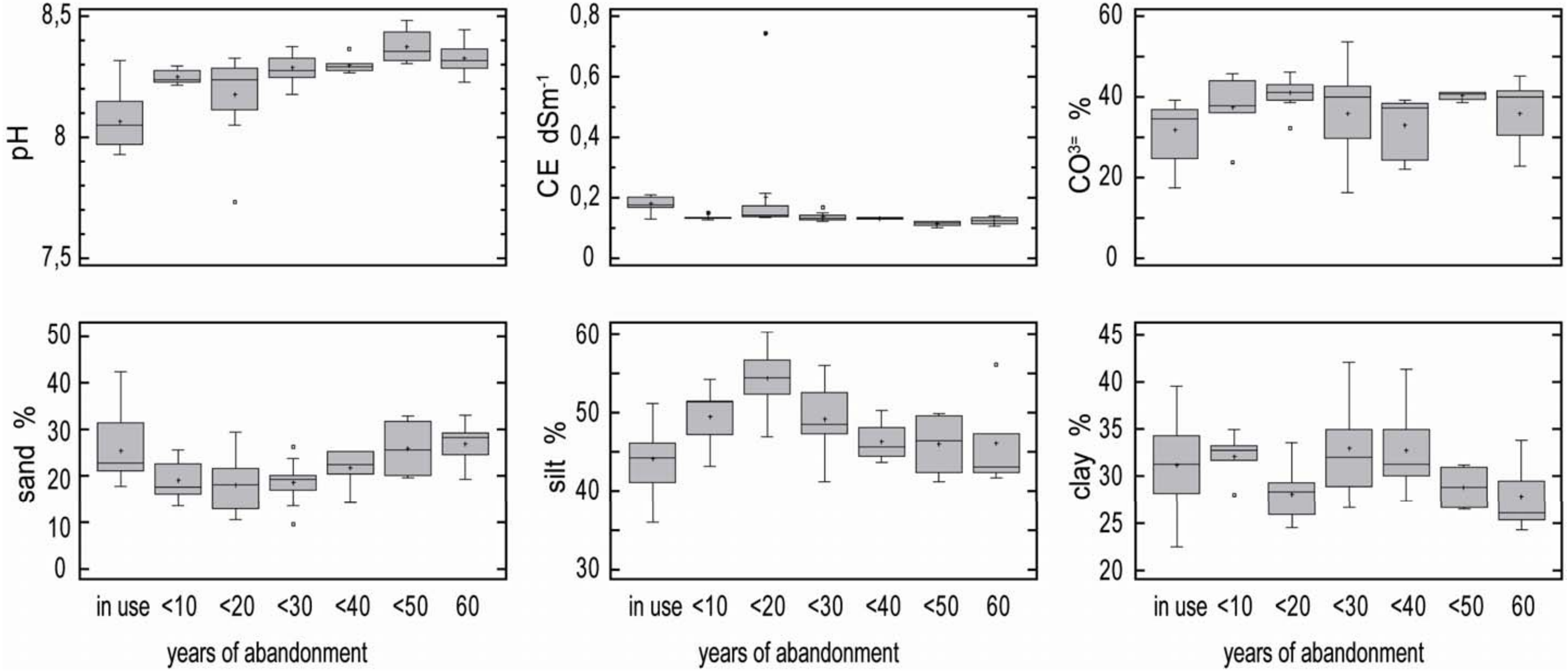
-40
-20
0
20
40
60
80
^{137}Cs gain/loss %
^{137}Cs gain/loss %


SOC %
0
1
2
3
4
in use
<10
<20
<30
<40
<50
60
years of abandonment
SON %
0
0,1
0,2
0,3
0,4
in use
<10
<20
<30
<40
<50
60
years of abandonment
SOC / SON %
0
4
8
12
in use
<10
<20
<30
<40
<50
60
years of abandonment


pH
8,5
8
7,5
CE dSm-1
0,8
0,6
0,4
0,2
0
CO3= %
60
40
20
0
sand %
50
40
30
20
10
0
silt %
60
50
40
30
clay %
45
40
35
30
25
20
in use
<10
<20
<30
<40
<50
60
years of abandonment