



27 nutrient redistribution. In the cultivated fields SOC and SON contents were higher and  
28 comparable to contents in the older abandoned fields, because the recovery of the  
29 natural vegetation after a long-term period of abandonment equalized the nutrient  
30 conditions in the cultivated fields that had regular additions of manure. In general SOC  
31 and SON percentages increased from the upper slope to the bottom slope of the fields  
32 with percentage increases ranging from 4 to 54 % and from 1.5 % to as much as 77 %,  
33 respectively. Similarly, significant increases of SOC and SON inventories (45 and 49  
34 %, respectively) were registered at the bottom slopes of longer fields by comparison  
35 with lower increases (33 and 30 %, respectively) in shorter and steeper fields. Soil  
36 deposition at the bottom slope as indicated by the  $^{137}\text{Cs}$  residuals was paralleled with  
37 increases in SOC and SON contents. Under the land use practices in the studied fields  
38 the bottom slope positions accumulate soil particles and act as sinks of soil carbon and  
39 nitrogen in these mountain agricultural landscapes.

40

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

43

#### 44 **1. Introduction**

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

51 loss of soil particles is often accompanied by depletion in soil nutrients with impacts on  
52 soil productivity.

53 Since Medieval times intensity of land uses has changed, thus in the Pyrenean  
54 mountains a great expansion of cultivated lands occurred at the end of the XIX<sup>th</sup> century  
55 and was followed by a process of land abandonment that started in the middle of the  
56 XX<sup>th</sup> century. The abandonment of marginal and non-productive lands occurred in  
57 successive pulses extending from the first part to the end of the XX<sup>th</sup> century. A main  
58 consequence of these rapid land use changes in the region was the increase in eroded  
59 surfaces that was paralleled with increases of sediment supplies to rivers and water  
60 bodies (Valero-Garcés et al., 1999; Navas et al., 2009). In mountain landscapes  
61 agricultural practices have been identified as main factors of soil loss (Navas et al.,  
62 2005a). In addition to erosion induced by tillage, the terrain physiography is another  
63 important factor affecting the soil redistribution and that of the nutrients in farmland  
64 landscapes (Ritchie and McCarty, 2008).

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

73 Soil erosion involves preferential removal of the fine soil particles and of light  
74 fractions like soil organic carbon (Bajracharya et al., 2000) and is one of the major  
75 processes affecting the redistribution of soil organic carbon (SOC) and nitrogen (SON)

76 in the landscapes (Lal, 2003). Soil erosion redistributes soil and SOC across agricultural  
77 landscapes (Zhang et al., 2006) and causes redeposition within the fields and net export  
78 (Ritchie and McCarty, 2003). Studies on spatial and temporal variation in SOC and  
79 SON are of great importance because of global environmental concerns. Agricultural  
80 practices affect the dynamics of SOC in soils (Quine and Van Oost, 2007; Van Oost et  
81 al., 2007), therefore understanding the mechanisms that control this dynamic is of  
82 interest to support sustainable agricultural practices and to promote the use of soils as  
83 carbon sinks to reduce the emissions of CO<sub>2</sub> (Lal 2004).

84 To assess soil erosion and redistribution fallout <sup>137</sup>Cs is being applied successfully in  
85 very diverse environments (e.g. Walling et al., 1999; Quine et al., 1994; Zhang et al.,  
86 2003, Martínez et al, 2009). In the region, studies by Navas et al. (1997, 2005a) used  
87 <sup>137</sup>Cs as soil radiotracer and evidenced the intense dynamics of the erosive/sedimentary  
88 process. The intensity of soil movement and its relationship with the process of land  
89 abandonment was assessed by McHenry et al. (1978) and Kachanoski (1987). For  
90 cultivated lands, several authors found clear links between soil redistribution processes  
91 and that of soil organic carbon evidenced by significant relationships between <sup>137</sup>Cs and  
92 SOC (Ritchie and McCarty, 2003; Li et al., 2006; Zhang et al., 2006; Ritchie et al.,  
93 2007). Therefore, fallout <sup>137</sup>Cs patterns could be used for assessing the dynamics of soil  
94 organic carbon and nitrogen on agricultural (Ritchie and McCarty, 2008, Wei et al.,  
95 2008) and also on rangeland landscapes (Martínez et al., 2010).

96 In the Aisa valley, that was most affected by land abandonment, a set of cultivated  
97 and abandoned small sized fields with different ages of abandonment, slope gradients  
98 and lengths were selected to assess variations in the contents of soil organic carbon and  
99 nitrogen .The distribution of these nutrients is analysed in different parts of the sloping  
100 fields together with that of grain size of soil particles and other general soil properties,

101 namely pH, electrical conductivity and carbonate content. In addition, data on fallout  
102  $^{137}\text{Cs}$  from a previous research are used to assess the association between soil  
103 redistribution at the different slope positions and that of soil organic carbon and  
104 nitrogen. Identifying if  $^{137}\text{Cs}$  and soil organic carbon and nitrogen have similar  
105 mechanisms of distribution in the landscape might allow association of the  $^{137}\text{Cs}$   
106 labelled areas of erosion or deposition with areas of depletion or enrichment of SOC  
107 and SON. Therefore, this work aims to assess if soil organic carbon and nitrogen  
108 derived from soil erosion at the upper positions of the slope results in the bury of  
109 amounts of SOC and SON at depositional sites at the bottom slope of the fields.  
110 Information derived from this research may help to identify sources and sinks of soil  
111 organic carbon and nitrogen and can be of interest to promote strategies for land  
112 conservation.

113

## 114 **2. Material and Methods**

115 The study was conducted on a south-facing slope of the Aisa valley (Central Spanish  
116 Pyrenees, Aragón) (Figure 1). In the valley altitudes range between 950 and 1400 m  
117 a.s.l. and traditional land uses are rainfed agriculture of cereal crops. The climate is sub  
118 Mediterranean type with Atlantic influence and mean annual precipitation of around  
119 1000 mm. The major socioeconomic changes that favoured migration from rural to  
120 urban areas was especially intense in the Pyrenean valley of Aisa and according to  
121 Lasanta et al. (1995), the total percentage of abandoned land in this valley reached 74  
122 %, one of the highest in the Pyrenees. The Calcaric Regosols are the main soil types  
123 developed on Eocene marls and sandstones at hillslope positions. The soils originated  
124 from colluvial processes are poorly developed with almost no horizon differentiation  
125 and soil depth ranges between 30 to 60 cm. Soils have high carbonate percentages (35

126 %), alkaline pH and organic matter contents around 3 %. The natural vegetation on the  
127 southfacing slopes is composed of *Quercus gr. Faginea* and submediterranean shrubs.

128 The criteria for land abandonment were distance to the villages, orientation, slope  
129 gradient and size of the fields and occurred in different periods during the XX<sup>th</sup> century.  
130 A set of fields both still cultivated and abandoned were selected to conduct this study.  
131 For the abandoned fields further selection was done to cover the time span of the  
132 characteristic abandoning period in the past century (c.a. 60 years). Under the secular  
133 traditional private tenancy and management existing in the area the contour of the small  
134 sized fields are made of stone walls. A total of 24 fields with different lengths and  
135 slopes were selected (Table 1). Fields have irregular shapes and their size range between  
136 0.1 and 1.5 has (Figure 1). In an attempt to analyse the effect of physiographic factors  
137 on the movement of nutrients and soil particles, the number of geomorphic elements  
138 that could be distinguished in each field was considered as a criteria for the groupment  
139 of the fields and they are named F2 and F3, respectively. In the F2 group (11 fields) two  
140 geomorphic positions were identified: upper slope and bottom slope. In the F3 group  
141 (13 fields) upper slope, midslope and bottom slope positions were identified. The F2  
142 group is composed by steep (median: 21° slope) and short (median: 47 m) fields, apart  
143 from field 1, a long and gentle field included within the F2 group as the midslope  
144 element was not evident. F3 fields are longer (median: 66 m) and gentler (median: 16°)  
145 than F2 fields. A summary of the characteristics of the fields is presented in Table 1.

146

## 147 2.1 Soil sampling and analyses

148 In each field, the sampling sites were distributed along transects to represent the  
149 geomorphic elements corresponding to the upper slope, midslope and bottom slope

150 positions. The length (m) and slope gradient (°) of the fields were measured to calculate  
151 the LS topographic factor of the RUSLE.

152 The number of sampling sites established in the fields varied depending on the size  
153 and shape of the field. In general, for characterizing each of the slope positions two  
154 rows were established for the F2 fields and three rows for the F3 fields. In each slope  
155 position the number of samples that were collected around 10 - 20 m apart varied  
156 depending on the size of the fields. Due to the irregular shape of the fields the number  
157 of samples collected ranged between 5 and 8 samples in larger fields, totalling 67 and  
158 82 sampling sites in F2 and F3 fields, respectively (Table 1). The sampling depth was  
159 the total soil depth, 30 cm at the upper and midslope positions and 60 cm at the sites  
160 located at the bottom of the slope where soil particles have accumulated. The sampling  
161 depths were also established to retain the entire <sup>137</sup>Cs profile. After comparison with the  
162 reference inventory for the area it is possible to discriminate if soil loss or gain occurred  
163 and to relate it with the content and inventories of SOC and SON at a particular point.  
164 Whole core samples were collected using a 8 cm automatic core driller and composite  
165 samples were created from the proportional mixture of the point samples.

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

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

177 General soil properties pH, electrical conductivity (EC) and carbonate content were  
178 analysed following standard procedures. The pH (1:2.5 soil:water) was measured using  
179 a pH-meter. Electrical conductivity ( $\text{dS m}^{-1}$ ) (1:5 soil:water) was measured using a  
180 conductivity meter. Carbonates were measured using a pressure calcimeter (CSIC,  
181 1976). Analysis of sand, silt and clay were done by using laser equipment (Coulter LS  
182 230). Samples were chemically disaggregated with sodium phosphate and then heated  
183 with hydrogen peroxide to guarantee total destruction of organic matter; ultrasounds  
184 were also applied to complete particle dispersion.

185 Estimates of the  $^{137}\text{Cs}$  residuals were done from data of  $^{137}\text{Cs}$  inventories in the  
186 composite samples from a previous research in the area (Navas et al., 1997). From the  
187  $^{137}\text{Cs}$  residuals (%), the amount of  $^{137}\text{Cs}$  that is gained or lost by comparison with the  
188 reference inventory for the area ( $4500 \pm 200 \text{ Bq m}^{-2}$ , established from 9 stable sites)  
189 can be estimated. Because of the close association of the radioisotope with the fine  
190 fraction of the soil, the gain or loss of soil can be inferred. The methodology for  
191 Caesium-137 analyses is well described in the literature (Walling & Quine, 1991).  
192 Gamma emission of  $^{137}\text{Cs}$  at 661.6 keV was counted for 30000 s (analytical precision of  
193  $\pm 8 \%$ ) by using a high resolution, low background, low energy, hyperpure Germanium  
194 coaxial detector coupled to an amplifier and multichannel analyser. The radioisotope  
195 content per surface area is expressed as inventories ( $\text{Bq m}^{-2}$ ).

196 To assess the significance of the effects of the slope position in the fields F2 and F3  
197 on SOC and SON at the sampling points we used an analysis of variance. To that end,  
198 the data were divided into F2 and F3 fields and into upper slope, midslope and bottom  
199 slope and  $\alpha$  was set to 0.05. Correlations were established to assess the relationships

200 between the length and slope of the fields, LS factor of the RUSLE with the SOC and  
201 SON contents. The effect of the variation of  $^{137}\text{Cs}$  residuals on the SOC and SON  
202 contents and inventories was examined through linear regression analyses.

203

204

### 205 **3. Results**

206 In the studied fields, the results for all samples collected in fields F2 and F3 indicate  
207 that soils are alkaline with a mean pH of 8.22 (sd = 0.15) ranging between 7.73 and 8.49  
208 (CV = 1.8 %). Salinity is very low, the mean value is  $0.16 \text{ dSm}^{-1}$  (sd= 0.08). The  
209 electrical conductivity is the soil property with highest variability and ranges between  
210 0.1 and  $0.74 \text{ dSm}^{-1}$  (CV = 54 %). The carbonate content is relatively high with a mean of  
211 36 % (sd = 8.2) and a range between 16 and 54 % (CV= 23 %).

212 The contents of soil organic carbon (SOC) and nitrogen (SON) in the composite  
213 samples for each of the studied fields are presented in Tables 2 and 3. The SOC  
214 percentages ( $\bar{X} = 1.54 \% \pm 0.35$ ) range between 0.91 and 3.09 % (CV = 22%) and the  
215 inventories ( $\bar{X} = 5.08 \text{ kgm}^{-2} \pm 1.49$ ) range between 2.8 and  $12.8 \text{ kgm}^{-2}$  (CV = 29%).  
216 The SON percentages ( $\bar{X} = 0.16 \% \pm 0.03$ ) range between 0.11 and 0.32 % (CV = 18  
217 %) and the inventories ( $\bar{X} = 0.54 \text{ kgm}^{-2} \pm 0.15$ ) range between 0.32 and  $1.32 \text{ kgm}^{-2}$   
218 (CV = 28 %). The mean of the ratio SOC/ SON is 9.4 (sd = 1.15) and varies between  
219 7.4 and 12.8. No significant differences were found in the means of SOC and SON for  
220 the F2 and F3 fields. These contents are low but fall within the normal ranges for  
221 similar soils in the region (Navas et al., 2005 b). By comparison with mean values of  
222 6.7 % found in similar natural soils under forest (López-Vicente and Navas, 2009) an  
223 important reduction of SOM levels was produced after the longterm and intense  
224 agricultural use in these fields. Depletion of the soil organic matter levels has been

225 pointed out as a main constraint for the recovery of degraded soils. Exhaustion due to  
226 deforestation and continuous cropping of the fields may rend difficult the recovery of  
227 the natural vegetation in the region (Navas et al., 2008).

228

### 229 3.1. Lateral variation of SOC and SON

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

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

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

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

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

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

274 In the F3 fields increases of mean SOC percentages and inventories (12 % and 45%,  
275 respectively) are higher than in the F2 fields (10 % and 33%, respectively). Similarly,  
276 increases of mean SON percentages and inventories are of 16% and 49%, respectively  
277 in the F3 fields and of 7% and 30%, respectively, in the F2 fields. Within the F2 fields  
278 the means of percentages and inventories of SOC and SON differed significantly ( $p \leq$   
279 0.05) for the upper slope and bottom slope positions. In the F3 fields the means of SOC  
280 and SON inventories were higher and significantly different at the bottom slope than at  
281 the other two slope positions, but significant differences were not found for the means  
282 of SOC percentages.

283 The higher increases of SOC and SON at the bottom slope in F3 fields coincides  
284 with a mean  $^{137}\text{Cs}$  gain of 18 % by comparison with a  $^{137}\text{Cs}$  gain of 17 % in the F2  
285 fields. In addition, clay percentages are also higher at the bottom slope of F3 fields  
286 (29.5 %) than at the bottom slope of F2 fields (26.8 %). Therefore, both higher  $^{137}\text{Cs}$   
287 gain and clay percentages explain the higher SOC and SON found at the bottom slope  
288 of F3 fields. The results are consistent with the fact that the length of the slope is related  
289 with higher erosion and this is consistent with the  $^{137}\text{Cs}$  gain that indicates that the sites  
290 at the bottom slope had experienced deposition of soil particles and of the associated  
291 nutrients.

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

297 The existence of a midslope element that frequently coincides with manmade  
298 terraces, many of which have collapsed, also appears to intervene in the soil

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

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

317 The lower levels of SOC and SON found at the upper slope positions of the fields, is  
318 coincidental with a loss of  $^{137}\text{Cs}$  (-16 % for the F2, -8 % for the F3 fields). Navas et al.  
319 (1997) found in this area a general and statistically significant increase of  $^{137}\text{Cs}$   
320 inventories from the upper slope to the bottom slope positions that indicated  
321 accumulation of soil particles at the lower parts of the slope. Organic matter is  
322 preferentially removed from the eroded soil, thereby depleting the contents of SOC at  
323 the erosion source. This can explain the relatively lower levels of SOC and SON at the

324 upper slope positions of the fields where field observations also identified some eroding  
325 patches. At the bottom of the slope there is a gain of  $^{137}\text{Cs}$  that suggests deposition of  
326 soil particles that remain trapped at the lower end of the fields. As a consequence SOC  
327 and SON percentages and inventories are highest at the bottom slope positions.

328 The relationships between the  $^{137}\text{Cs}$  residuals, that are expressed as percentage of the  
329  $^{137}\text{Cs}$  gained or lost and the percentages and inventories of SOC and SON, with stronger  
330 correlations for SOC and SON inventories, indicate that the levels of nutrients increase  
331 for increasing percentages of  $^{137}\text{Cs}$  gain (Table 6). The statistically significant  
332 relationships ( $p \leq 0.05$ ) for the F2 and F3 fields, with the SOC and SON inventories,  
333 and also with SOC and SON percentages for the F3 fields confirm that a gain of  $^{137}\text{Cs}$   
334 and therefore of soil particles is paralleled with a gain in SOC and SON (Figure 3).  
335 According to Lal (2003) eroded sediments are enriched in organic matter in a ratio  
336 greater than 1 because organic matter concentrates in the topsoil and is preferentially  
337 removed by runoff. Martinez et al. (2010) also found strong and significant  
338 relationships between  $^{137}\text{Cs}$  and SOC for previously cultivated creek flats in a region  
339 of Australia. However, the relationships between  $^{137}\text{Cs}$  residuals and SOC and SON  
340 percentages are not statistically significant for the F2 fields which might be due to a  
341 lower number of observations and to the more limited soil redistribution within these  
342 fields in comparison with the F3 fields.

343 In the F3 fields although the relationships between clay percentages and SOC and  
344 SON percentages and inventories were not significant they showed the expected direct  
345 trend (Table 6). This was not the case for the F2 fields and could be also the reason for  
346 the lack of significance in the relationships of SOC and SON percentages with the  $^{137}\text{Cs}$   
347 residuals. The lack of significance in the relationships between clay and SOC and SON  
348 that show a negative trend could be due to some export of the finest soil fraction with

349 high runoff events which might trespass the stone walls. Also enrichment in sand  
350 contents at bottom slopes is associated with selective deposition of coarser particles at  
351 accumulation sites. In addition, because, F3 fields are longer they are more likely to trap  
352 clays inside the fields than in the shorter and steeper F2 fields.

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

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

371 The homogeneity of the studied fields that have similar soil types, parent materials  
372 and slope orientation can be the reason for the similar behaviour of SOC and SON.  
373 Their accumulation at the lower parts of the fields in close link with that of soil reflects

374 that topography was a key factor affecting the pattern of the lateral distribution of SOC  
375 and SON. Ritchie and McCarty (2008) and Martinez et al. (2010) also found strong  
376 links between soil redistribution and soil organic carbon concentrations suggesting that  
377 they move along similar physical pathways in agricultural soils.

378

### 379 3.2. Temporal evolution of SOC and SON after land abandonment

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

385 An analysis of variance in function of the age of abandonment was performed  
386 for SOC and SON and the results indicated statistically significant differences at the  
387 95% confidence level between the means of the nutrients in function of the age of  
388 abandonment for each of the 10 year period groups. However, differences can not be  
389 related with soil movement in the fields as results of an ANOVA for the  $^{137}\text{Cs}$   
390 inventories in function of the age of abandonment did not show statistically significant  
391 differences for the  $^{137}\text{Cs}$  inventory means in each of the 10 year period groups.

392 The box and whisker plots in Figure 4 shows that SOC was highest in the fields that  
393 are in use and that their means are not significantly different from mean SOC  
394 percentages in fields abandoned 40, 50 and 60 years ago. However, mean SOC  
395 percentages differed significantly from the means in fields abandoned 10, 20 and 30  
396 years ago. The reason could be that fields that are cultivated are fertilized regularly with  
397 manure and therefore SOC contents are high. Then, after land abandonment a depletion  
398 period follows until the decreasing trend is reversed when the recovery of the natural

399 vegetation is substantial enough as to incorporate organic matter in the natural plant-soil  
400 cycle. The SOC percentages start increasing after 30 years of abandonment and after  
401 more than 60 years of abandonment SOC reaches similar contents as those found in the  
402 cultivated fields that are fertilized. Total nitrogen also had highest mean values in the  
403 fields that are still in use and they were significantly different from the means of the rest  
404 of the fields, apart from the 10 and 40 years abandoned fields. However mean SON  
405 values for the longest periods of abandonment did not reach the contents in the fields in  
406 use. The ratio SOC/SON had the lowest values for the more recently abandoned fields  
407 (10 and 20 years) and differed significantly from the older fields (50 and 60 years).  
408 With time, there is trend to reach the equilibrium and the values closer to the optimum  
409 value of this ratio (10) were found in the oldest fields that are only comparable to the  
410 high ratio found in the cultivated fields that are fertilized regularly.

411 For the other soil properties some variations were found in function of the time of  
412 land abandonment (Figure 5). The pH means tend to increase for longer periods of land  
413 abandonment, and the highest values were found in the fields abandoned 50 and 60  
414 years ago. The contrary was observed for the EC means that progressively decreased for  
415 increasing periods of land abandonment with the EC lowest values in fields abandoned  
416 50 years ago. The reason of the EC trend can be explained because after land  
417 abandonment the addition of fertilizers ceased and as a consequence of leaching salinity  
418 is reduced with time. The means of carbonate contents do not follow this pattern as  
419 contents increased since the onset of land abandonment till the 20 years period of land  
420 abandonment. However, the variation in carbonate content is likely to be associated  
421 with the grain size distribution because silt is the fraction more abundant in the soils  
422 (around 50 %) and silt material is of carbonatic nature. As can be seen in Figure 5 the  
423 means of silt content increased for the same period and then slightly decreased for

424 longer periods of land abandonment. The opposite pattern was found for the sand  
425 contents. The means of clay percentages indicated a trend to decrease for longer time of  
426 land abandonment since the 30 years period of abandonment. The relatively low clay  
427 contents in the oldest fields may be the reason for the moderate SOC and SON increases  
428 observed in these fields. In addition, in the oldest fields the successional changes that  
429 had occurred in the vegetation led to the total disappearance of *Genista scorpius*  
430 produced after reaching a maximum development (Montserrat, 1990). This may also  
431 contribute to explain the relatively low increases of SOC and SON in the oldest fields.

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

435

#### 436 **4. Conclusions**

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

445 The contents of SOC and SON are directly related. Increases of SOC from the upper  
446 slope to the bottom slope are paralleled with increases of SON. Soil deposition at the  
447 bottom slope as shown by fallout  $^{137}\text{Cs}$  inventories is paralleled with increases in SOC  
448 and SON contents. Less common SOC decreases occur in some sites at the bottom of

449 the slope with no evidence of soil deposition therefore, SOC depletion is associated to  
450 loss of fine soil particles.

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

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

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

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

474

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477

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580

581 **Figures**

582

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

586

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

589

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

592

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

595

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